U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Manufacturing Roadmap

Solid-State Lighting Research and Development

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Prepared by Bardsley Consulting, Navigant Consulting, SB Consulting, and SSLS, Inc.

DISCLAIMER

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SSL Manufacturing Roadmap

SOLID STATE LIGHTING RESEARCH AND DEVELOPMENT

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A recent U.S. Department of Energy (DOE) analysis update by Navigant Consulting, Inc. (Navigant) reviewing the adoption of solid-state lighting (SSL) technology in the U.S. [1] concluded that annual source energy savings from light-emitting diode (LED) lighting in 2013 more than doubled from the previous year to 188 trillion British thermal units (BTUs), which is equivalent to an annual energy cost savings of about $1.8 billion. While these current savings are significant market penetration is still quite modest. For one high-profile form factor, A-lamps, it was estimated that only about one percent of the installed base is LED lamps, but growth is accelerating rapidly. From 2012 to 2013, it was found that the U.S. installed base of LEDs in general lighting applications had more than doubled to about 105 million units. Navigant further concluded that the 188 trillion BTU savings represents only a tiny fraction of the total potential energy savings of about 4.1 quadrillion BTU (quads) assuming complete adoption of SSL. While widespread adoption may be several years off, the potential highlights the importance of developing a robust, high-capacity manufacturing capability for SSL. Market adoption is likely to accelerate as prices continue to fall and unit sales are expected to increase at a much faster rate than revenues.

In response to this energy-saving opportunity, the DOE SSL manufacturing initiative was launched in 2009 to support reductions in SSL manufacturing cost, improve product quality and consistency, and establish a strong SSL manufacturing base in the U.S. This is the sixth edition of the Manufacturing Roadmap, which is intended to provide a guide to key manufacturing research and development (R&D) priorities to continue and improve capability and to establish a strong role for the U.S. in SSL production.

The DOE SSL manufacturing initiative has supported almost $100[a] million in manufacturing R&D projects directed at identified priorities. Some previous notable projects include KLA-Tencor's development of the Candela 8620 inspection system and Veeco Instruments' development of the MaxBright^{TM} metal organic chemical vapor deposition (MOCVD) multi-reactor system [2]. Current projects include Cree's development of lower cost integrated LED luminaires, Philips Lumileds' development of patterned sapphire substrate technology for lighting caliber LEDs, and OLEDWorks' development of organic light-emitting diode (OLED) deposition technology for OLED lighting products [3]. DOE-supported SSL manufacturing R&D projects cover much of the value chain of SSL production, including process improvements, manufacturing equipment, materials, testing, and designs for low cost.

To identify priority tasks appropriate for funding, DOE engaged the LED community beginning with a "Round-Table" meeting of invited experts to review the state of LED-SSL manufacturing technology and identify areas for improvement. This meeting took place in Washington, DC on February 11, 2014. For OLEDs, the conversations began at a more open format meeting that took place in Rochester, New York, on October 1, 2013, to review the state of OLED SSL technology

[a] Includes cost share by project performer.

and identify opportunities for R&D from core research to manufacturing R&D. These meetings were followed by the annual SSL Manufacturing R&D Workshop, which was held May 7-8 in San Diego, CA [4]. This year a post-workshop conference call was also held among the OLED participants to further refine the priority research topics. The outcomes are summarized below and reflect a few key themes that arose during the discussions:

- For LED-based lighting products, consistently achieving the targeted color point adds cost and complexity to the luminaire manufacturing process, especially where the application demands tight color control.
- For LED-based lighting products (and probably OLED as well), long-term color stability is still poorly understood and mitigation approaches add to the cost of LED lighting products. The ability to understand and predict color shift over time would increase consumer confidence in LED lighting products and could simplify the manufacturing process, thereby reducing manufacturing cost.
- Luminaire manufacturing continues to change dramatically in response to the new technology, with less emphasis on the lamp-fixture paradigm and increasing emphasis on integrated luminaires to minimize cost and maximize efficacy.
- Highly flexible luminaire and module manufacturing will be needed to address the rapidly expanding market. That is, to be able to accommodate the enormous variety of designs demanded by customers for multiple applications, lines will need to be efficient and cost-effective, even with relatively low numbers for any given code. This may call for innovative manufacturing methods and equipment.
- More attention needs to be paid to the manufacturing of phosphors/down-converters and the efficient application of these materials within the LED package. There are opportunities to reduce cost, improve efficacy, improve color quality, increase light output, and simplify the manufacturing process.
- There is an opportunity for the domestic OLED community to work together to create a viable U.S. manufacturing infrastructure for OLED lighting products and promote consumer acceptance of OLED lighting products. Larger volume production is needed to exercise the supply chain and manufacturing processes in order to identify weaknesses and opportunities.
- The OLED community is preparing to introduce products for lighting by working to understand the needs of luminaire manufacturers and lighting designers and by understanding barriers to adoption that have slowed down LED adoption.
- For OLEDs, solution and vapor deposition approaches are both being explored and hybrid approaches are common. Though commercial OLED panels are mostly based on vapor deposition techniques, major efforts are underway to promote solution processed panel production.

Right now, the primary challenge for LED lighting is to ramp up production and continue to drive down costs, while maintaining product quality and consistency. The emerging challenge is to demonstrate to the customer the added value offered by LED technology, whether it is reduced energy consumption, extended lifetime, or added functionality, and to avoid customer disappointments. The expansion of LED lighting manufacturing capacity will, in the short term, require the refinement of existing manufacturing approaches. Longer term, it will require the introduction of innovative approaches to lighting product design and manufacturing.

The biggest challenge for OLEDs is to develop acceptable, cost-effective manufacturing processes and build demand by identifying lighting applications that play to the strengths of OLED technology. OLEDs need to translate some recent successes in efficacy and other performance parameters into cost-effective manufacturing, which is again likely to require novel approaches that go beyond what is being done for manufacturing of OLED displays.

Global Manufacturing

Lighting is, and always has been, a global market. Today, as SSL technology gains market share, the demand for lighting continues to grow throughout the world, but particularly in Asia. The transition to SSL and the growth in lighting demand, coupled with the rapid growth in LED backlighting for displays, has led to a rapid expansion of LED wafer manufacturing capacity in Asia over the last few years. However, wafer manufacturing capacity does not tell the whole story of the LED lighting supply chain.

Most of this fabrication capacity is used to produce LEDs used in displays, but the capacity does influence the lighting supply chain. The deployment of MOCVD equipment and the infrastructure that supports packaging of LEDs provides the basic infrastructure for the production of LEDs, and there is a growing trend toward using display type mid-power LEDs for lighting applications. This growth in capacity has created a strong market for LED production tools. These tools represent a significant market and provide a promising opportunity for North American companies.

Packaging of LEDs has continued to be centered in Asia, partly because of a strong existing semiconductor packaging infrastructure, but also influenced by the availability of low-cost labor, low-cost tooling and tax incentives. Assembly of replacement lamps, built on a similar infrastructure, has also strengthened in Asia.

It remains to be seen what will happen with integrated luminaires. These products are larger and heavier than lamps or LED packages, and also tend to be more specialized by region. Accordingly, there is incentive to develop local manufacturing capability for this segment of the value chain. There are, in fact, thousands of local luminaire makers from the legacy technologies worldwide, some of which may not survive the transition to SSL. However, many will survive and new companies are appearing as the market grows – many of which have origins in North America.

For OLEDs, the demand for small OLED displays for portable devices has driven Asian companies, especially in Korea, to make significant investment in OLED manufacturing. While OLED lighting manufacturing will be quite different, these display investments have influenced the market both in terms of equipment and materials costs and performance. Currently, there is a high barrier to entry for OLED manufacturing, which may discourage smaller companies from addressing this market. However, alternative, lower capital cost approaches are being explored for OLED panel manufacturing for lighting, and, if successful, and could help to spur U.S. participation. OLED luminaires will be subject to similar considerations as LED luminaires, as noted above.

LED Manufacturing R&D Priorities

During the Roundtables, Manufacturing Workshop, and internal DOE discussions, three Manufacturing R&D tasks for LED-based luminaire manufacturing were prioritized for 2014. These choices for LED Manufacturing are listed by title and brief descriptions are provided below.

M.L1	**Luminaire Manufacturing** Support for the development of flexible manufacturing of state-of-the-art LED modules, light engines, and luminaires.
M.L3	**Test and Inspection Equipment** Support for the development of high-speed, high-resolution, non-destructive test equipment with standardized test procedures and appropriate metrics.
M.L7	**Phosphor Manufacturing and Application** Support for the development of efficient manufacturing and improved application of phosphors (including alternative down converters) used in solid-state lighting.

OLED Manufacturing R&D Priorities

There were three OLED Manufacturing R&D tasks identified for 2014 as a result of the OLED discussions. The selections for the development of OLED manufacturing technology are listed below.

M.O1	**OLED Fabrication Equipment** Support for the development of manufacturing equipment enabling high-speed, low-cost, and uniform deposition of state-of-the-art OLED structures and layers.
M.O3	**OLED Substrate and Encapsulation Manufacturing** Support for the development of advanced manufacturing of low-cost, integrated substrates and/or encapsulation materials.
M.O5	**OLED Panel Manufacturing** Support for the development of manufacturing processes for practical OLED panels.

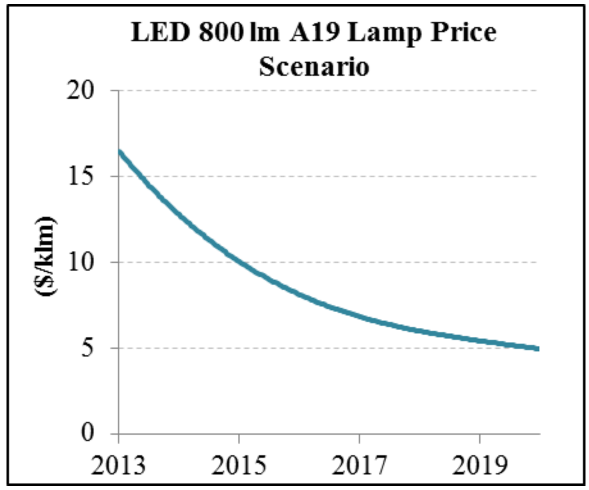
Overall Cost Projections and Contributions to Cost Reduction

Since its inception, the DOE SSL manufacturing initiative has emphasized the importance of significantly reducing costs in order to speed adoption and the resulting energy savings. At this stage of the technology development, LED product prices have fallen sufficiently such that adoption has begun to accelerate rapidly. While OLED prices are still out of range for most buyers, prices (in $/klm) are falling rapidly, seeing about a 40% decrease from 2013 to 2014.

LED Lighting

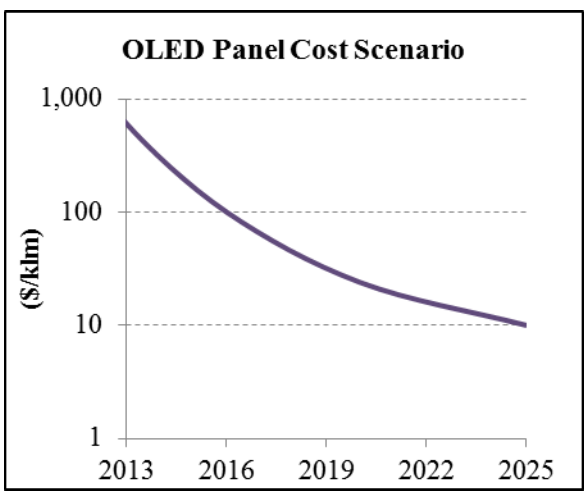
Current prices for qualified high-power packages are around $5/klm for cool white and $6/klm for warm white [5]. However, this only tells part of the story. LED package designs have expanded significantly over the past few years to match the product demands for specific lighting applications. One particular trend is the introduction of high-performance, low-cost, mid-power packages originally developed for flat-screen displays and televisions. Such packages are not compatible with DOE's qualification criteria (originally developed for high-power packages) but in a practical sense offer prices as low as $1/klm.

Replacement lamp costs, especially for the critical A19 lamp segment, have continued to fall. These reductions are partly due to lower LED prices but also to the introduction of improved manufacturing materials and methods. No one cost factor dominates, as discussed in Section 1.3.2, and cost reduction has been driven by system considerations such as improved design for manufacturing and assembly. Replacement lamp costs fell by an estimated 22% from 2013 to 2014, and retail prices have followed suit as shown in the figure on the right.



OLED Lighting

OLED lighting is at a different stage. While OLEDs continue to be used for small displays, particularly in smartphones and small tablets, a direct impact on the cost of OLED lighting products is not yet evident. Partly this is because OLED lighting manufacturing is still evolving and the device architectures and performance requirements are different than those for displays. Further, the production scale is much smaller than for displays, so the experience, equipment, and infrastructure of display fabrication cannot be readily adopted. The small scale and newness of the OLED lighting industry complicates cost projections, which involve many assumptions that are not easily tested.



However, it is possible to envision a scenario whereby OLED lighting panels may achieve viable costs within the next decade or so. To achieve a cost of $10/klm (corresponding to about $100/m^2) will likely require several key assumptions and strategies, among them:

- Continued expansion of the OLED display market will be necessary to enable material costs to fall to the target levels for lighting.
- Dramatic improvements in light extraction will be made, which will yield higher efficacies as well as increase the light output per unit area. This can lead to reduced materials usage and cost as smaller panels can provide the necessary light.

- Low-cost substrates and encapsulation materials will be developed.
- Manufacturing will be in relatively small substrate sizes in order to minimize the capital outlay to make viable pricing possible. As demand increases, manufacturing methods will be scalable to create the desired supply.
- Moderate scale, small substrate manufacturing provides an opportunity to achieve improvements in process efficiency before major capital investments are made.
- Greater clarification concerning the relative merits of the several alternative manufacturing methods and the market acceptance of OLED lighting must be obtained before commitments are made to high-capacity production lines.

The cost estimate shown in the figure above is not a target or prediction of where OLED costs may be in the next few years, but rather an indication of the kind of movement and action that may be necessary to realize a viable OLED lighting market. In fact, it may be necessary to accelerate these cost reductions by five years or so to realize substantial market shares and corresponding energy savings for OLEDs. Early cost drivers will be related to emitting and packaging materials inputs and the design of efficient small-scale processes. Later, the design of cost-effective, larger scale tools and packaging issues may become more significant. There may be other paths as well; this is just one example but all are likely to be similarly risky, and progress on OLED price reduction and sales volume has been limited so far. A critical ingredient to success may be the willingness of the industry to agree on a set of processes and design assumptions that will allow the players to move forward in concert towards a common goal.

Since there is not a significant OLED luminaire market, we have not attempted to develop a cost reduction track for a full OLED luminaire. However, because of the very high cost of panels, they will dominate OLED luminaire costs for some time. Prices in the very near term will largely be driven by highly decorative and specialized fixtures.

1 OVERVIEW OF SSL MANUFACTURING STATUS

This document considers the manufacturing of solid-state lighting (SSL) products. SSL involves the use of light-emitting diodes (LEDs) or organic light-emitting diodes (OLEDs) for the production of general illumination lighting. The technological development of LEDs, OLEDs, and SSL products has developed rapidly over the last two decades. Manufacturing developments have accelerated to keep pace with these technological developments and have enabled the introduction of a broad range of high-efficiency general illumination lighting products. Despite the success to date, further work is required to continue to reduce manufacturing costs to accelerate adoption, and to ensure products meet the levels of quality and reliability demanded by the markets. This chapter provides a general status for of the manufacturing supply chains for LED- and OLED-based lighting, as well as a general discussion of geographical production trends for SSL.

The adoption of SSL is also accelerating. While in some applications, such as A-type replacement lamps, SSL accounts for about 1% of installations, for others it is already becoming even more significant. According to an analysis conducted by Navigant Consulting, Inc. (Navigant) on adoption rates for LED lighting in the U.S., LED lamps made up about 16% of MR16 type installations in 2013, and 7% of area and roadway fixtures [1]. Market share is rapidly increasing across all application areas. Due to its efficiency, low cost of ownership, controllability, and lifetime, LED lighting has the potential to become the dominant lighting technology, accounting for the majority of the lighting market within the next 20 years. This would represent a fundamental shift in the lighting market and require very rapid growth in SSL production capabilities. The manufacturing processes for LEDs and LED-based lighting products have quickly evolved into large-scale production processes. However, LED and LED-based lighting manufacturing is still developing compared to the manufacturing processes used for similar end products like semiconductor integrated circuits, consumer electronics, or conventional lighting fixtures. At this early stage in the maturation of LED-based SSL there is an opportunity to develop new manufacturing tools, materials, and techniques that can dramatically impact the cost and quality of LED-based lighting and define the manufacturing supply chain. The U.S. is currently well positioned with respect to LED epitaxy, luminaire manufacturing, and manufacturing equipment, which should enable the growth of a broader, well-defined, domestic manufacturing infrastructure that could provide long-term domestic manufacturing jobs and other benefits.

OLED-based SSL technology is much less developed than LED-based SSL. OLED lighting offers intriguing potential benefits in terms of lighting quality, functionality, performance, and cost. OLEDs are fundamentally large-area, low-brightness, thin-form factor light sources which could complement high-brightness, small-area LED light sources. OLEDs also have the potential for low cost roll-to-roll (R2R) type production. In Japan, Konica Minolta is facing the challenges of turning this promise into reality head-on by a massive investment in a $100 million R2R production facility that plans to start production of flexible color tunable and white OLED panels this fall.

The greatest impediment to market acceptance of OLED lighting is the extremely high cost of the currently available panels. A typical panel has a light-emitting area of about 100 cm^2 and produces up to around 100 lm at a price of roughly $50 or more. This equates to a normalized price of around $500/klm as compared to prices of a few $/klm for LED sources. Furthermore, almost all of the panels are rigid with simple, planar shapes. OLED luminaire manufacturers are attempting to add value by embedding multiple panels into stylish fixtures, but this adds even more cost. The resulting luminaires are acceptable only for applications in which the decorative value is more important than the light output.

The development of OLED technology and manufacturing may be accelerated by the use of OLED displays in mobile devices, currently the largest market, as well as other developing applications such as television displays. While important differences in the technology and performance requirements could limit the applicability of OLED display developments to lighting production, advancements in OLED production technology could nevertheless greatly impact the performance and cost of OLED products and influence the geography and structure of the OLED supply chain.

1.1 SSL Manufacturing Supply Chain

Both LED and OLED manufacturing processes can be generally defined by a sequence of reasonably independent manufacturing steps. These manufacturing steps are supported by the supply of manufacturing equipment, materials, and testing equipment. The combination of the manufacturing processes, equipment, materials, and testing constitute the manufacturing supply chain.

This document regularly refers to the manufacturing supply chains for LED and OLED-based SSL to discuss the cost, quality, and domestic manufacturing impacts. The supply chains shown below represent the general situation for LED and OLED-based SSL manufacturing right now, but these supply chains will continue to evolve and mature. For example, a vertically integrated manufacturer might currently handle a number of these processes internally; however, as the manufacturing industry matures, it is common for the supply chain to become more disaggregated for optimum manufacturing efficiency. In addition, the manufacturing supply chain will be impacted by developments in technology and product design and can also be impacted by product distribution including geographical or regulatory considerations.

1.1.1 LED-Based SSL Manufacturing

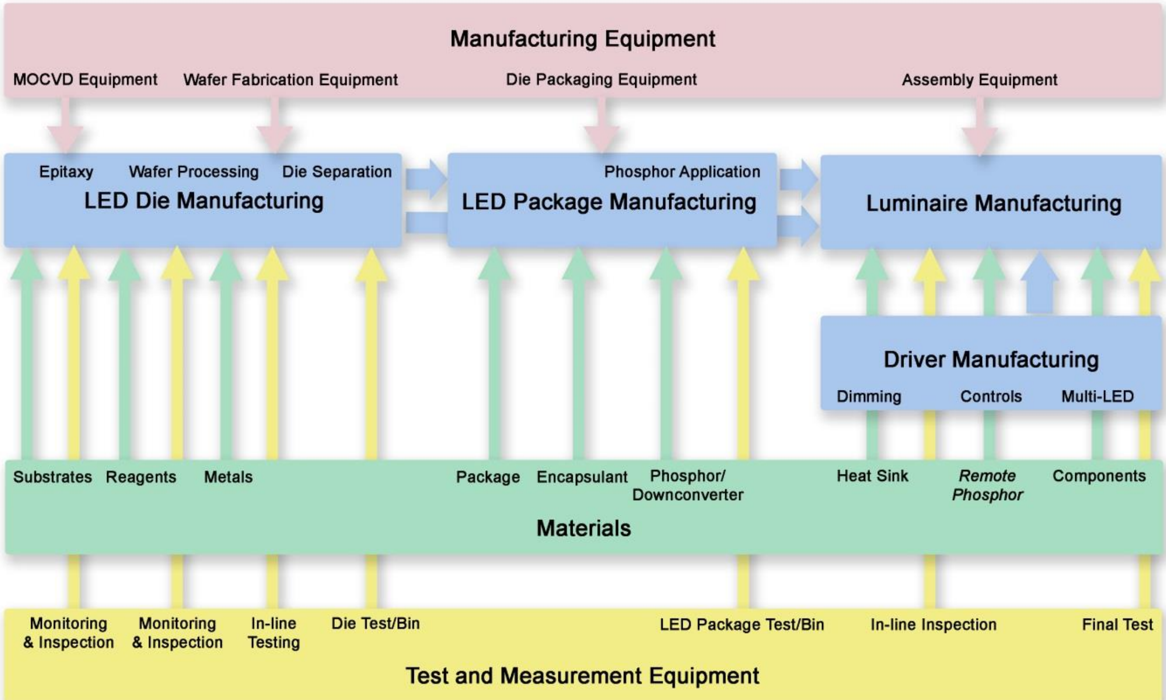


Figure 1.1 LED-Based SSL Manufacturing Supply Chain

Figure 1.1 is a schematic representation of the LED-based SSL manufacturing supply chain. The blue-shaded boxes and blue arrows describe the main manufacturing flow. The supporting elements of the supply chain are broken down into manufacturing equipment, materials, and test and measurement equipment. These supporting elements feed into the main manufacturing flow as indicated by the relevant arrows.

The manufacturing process for LED-based luminaires begins with LED die manufacturing, consisting of growth of the LED wafer by metal organic chemical vapor deposition (MOCVD), processing of the LED wafer by mostly conventional semiconductor processes, and separation of the LED wafer into individual LED chips. The next step is typically to mount the LED die into LED packages, including the deposition of phosphor material to convert the blue LED emission to white light. Finally, the LED packages are integrated into the end luminaire or lamp product. An alternative approach might involve dispensing with the intermediate LED package stage and mounting the die directly onto a circuit board or heat sink. The luminaire also requires the integration of a driver, heat sink, optical components, and general mechanical structure.

1.1.2 OLED-Based SSL Manufacturing

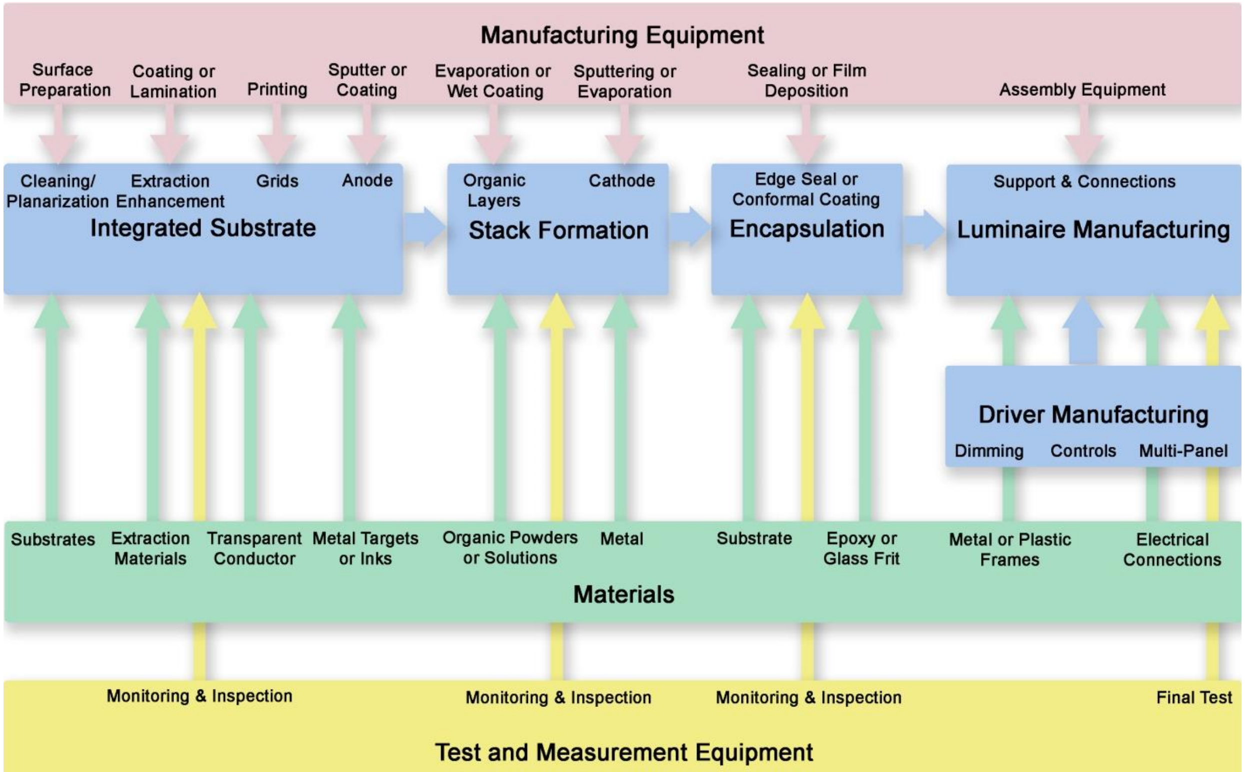


Figure 1.2 OLED-Based SSL Manufacturing Supply Chain

Figure 1.2 is a schematic representation of the OLED-based SSL manufacturing supply chain. Similar to the LED version, the supply chain is broken down into a central manufacturing process flow with supporting equipment and materials. The OLED manufacturing process begins with the growth substrate. The growth substrate, typically glass, contains planarized, transparent anode material and, possibly, current spreading grids and surface texturing on one or both surfaces for light extraction. The OLED stack is then deposited on the substrate with a metallic cathode. The OLED stack includes organic electron and hole charge conduction and emission materials. The next step is to encapsulate the OLED stack to protect the layers from degradation caused by oxygen or moisture. At this point the encapsulated OLED stack is typically referred to as a panel, which can be directly integrated into a luminaire. Luminaire integration includes mechanically attaching the required number of OLED panels for the application and electrically connecting a driver.

1.2 Global and U.S. Production

SSL manufacturing involves a truly global supply chain. An important objective for this program is that the economic benefit derived from such work benefits the U.S. economy to the greatest extent possible. Specifically for the SSL program, that objective translates into maintaining a significant manufacturing role for the U.S. in the global lighting market. Manufacturing must meet the rapidly expanding global demand for SSL products, for which some of the largest and fastest growing markets are in regions outside North America. As an example, Figure 1.3 shows the anticipated growth in unit sales for LED luminaires by geographical region. The compound annual growth rate (CAGR) in unit sales from 2013 to 2018 is around 17% and for revenues it is expected to be around 12%. A similar trend is expected for LED lamps but the CAGR in unit sales over the same time period is projected to be much higher at around 50% and for revenue growth is expected to be around 21% [6]. Meeting the market demand for regions outside of North America often means establishing some manufacturing presence in that region; many of the larger manufacturers have relocated a significant portion of their manufacturing activity to Asia in order to access growth in that region. Ultimately, the optimum geographical distribution of the manufacturing operation will depend on many factors, including supply chain infrastructure, control of intellectual property, product design, tax environment, regulation, shipping and distribution costs, and labor costs. Many of these considerations still favor a significant domestic manufacturing base for both LEDs and OLEDs, and there is an exigent opportunity to continue to grow the domestic manufacturing infrastructure.

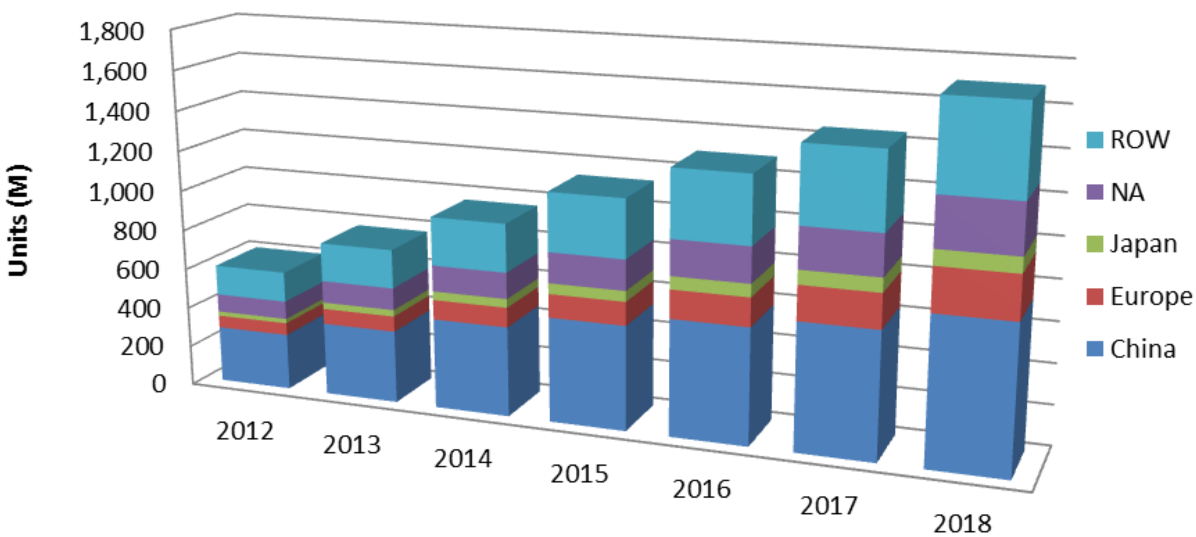


Figure 1.3 Growth of LED Luminaire Unit Sales by Region, 2012 to 2018 (17% CAGR)
Source: Smallwood, Strategies Unlimited, DOE SSL Manufacturing R&D Workshop, San Diego, 2014

The time for developing a robust domestic SSL manufacturing infrastructure is now, as SSL technology is projected to dominate the lighting market within 10 years. Figure 1.4 also shows that by 2020, LED light sources are projected to account for almost 50% of all lamp unit sales. This represents an enormous transition in the lighting market and demonstrates the opportunity for LED products in any type of lighting form factor.

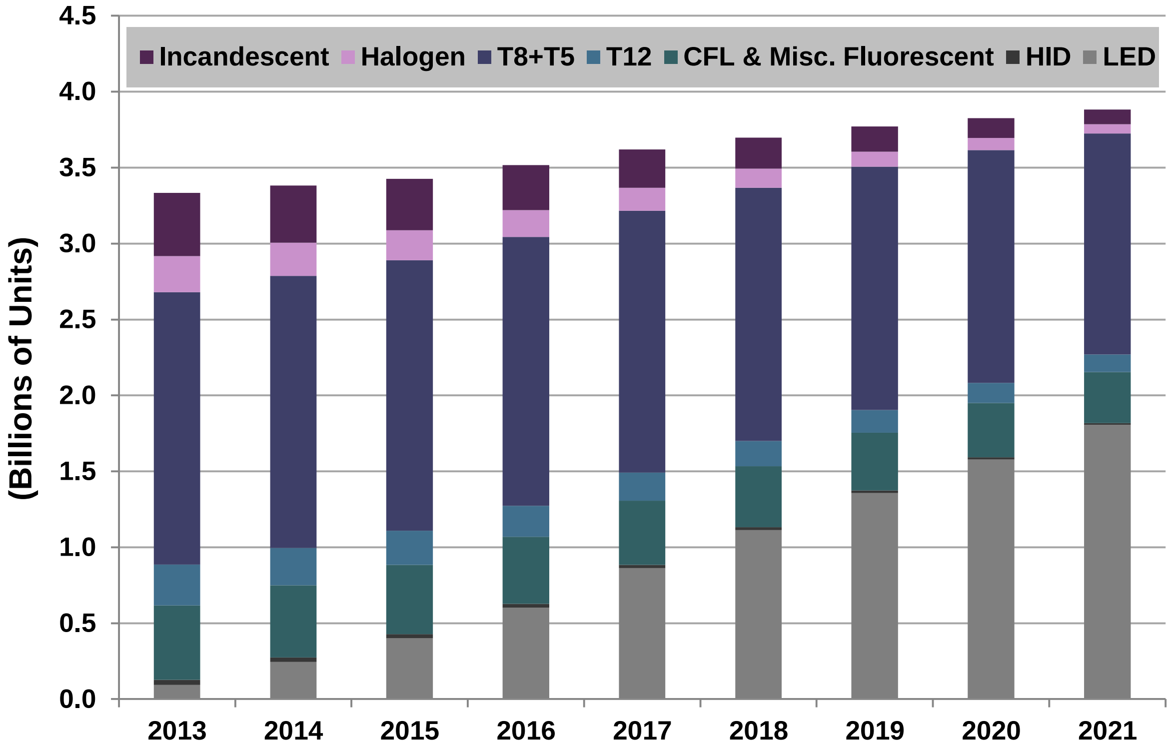


Figure 1.4 Forecast of Shipments of Commercial Lamps and Luminaires, 2013-2020

Source: Energy Efficient Lighting for Commercial Markets. Prepared by Navigant Research, 2013.

1.2.1 LED

LED, lamp, and luminaire manufacturing are global enterprises with a global supply chain. Some geographical production trends can be identified; however, many of the input materials and semiconductor processing tools are produced worldwide. Table 1.1and Table 1.2 highlight the global nature of SSL manufacturing by listing some of the key companies in each major geographical region involved in the manufacturing of LED-based SSL products and in the supply of equipment and materials to that market. These tables categorize geographical location based on company headquarter location and may not accurately reflect the balance of manufacturing activity.

Table 1.1 The LED Supply Chain: LED Die, LED Package, and Luminaire Manufacturers

Supply Chain	North America	Europe	Asia
Die Manufacturing	• Cree • Philips Lumileds • Bridgelux • Soraa • SemiLEDs • Luminus Devices	• OSRAM Opto Semiconductors • Optogan • Plessey Semiconductors	• Nichia • Toyoda Gosei • Toshiba • Sharp • Epistar • SemiLEDs Optoelectronics • TSMC • OptoTech • FOREPI • Everlight • Lumens • Kingbright • Samsung • LG Innotek • Seoul Semiconductor • Elec-Tech Opto • Epilight • HC SemiTek • Sanan Optoelectronics
LED Package Manufacturing	As above	As above	As above and: • Lite-On • Unity Opto • Lextar • Nationstar • Shenzhen Jufei • Honlitronic • Refond
Luminaire Manufacturing	• GE Lighting • Eaton/Cooper Lighting • Hubbell Lighting • Acuity Brands • Cree • Lighting Science Group • Soraa	• Philips • Osram Sylvania • Zumtobel	• Panasonic • Toshiba • Sharp • LG • Samsung • Kingsun • Zhejiang Yankon • Shenzhen Changfang • Opple Lighting • PAK Corp • Nationstar • NVC Lighting Tech Corp • FSL

Table 1.2 The LED Supply Chain: Equipment and Materials Suppliers

	Supply Chain	North America	Europe	Asia
Equipment Suppliers	**Epitaxial growth**	• Veeco Instruments	• Aixtron	• Taiyo Nippon Sanso
Equipment Suppliers	**Wafer processing**	• Plasma-Therm • Lam Research • Ultratech • JPSA • Temescal	• Oxford Inst. Plasma Tech • EV Group • SUSS MicroTec • Logitech	• Nikon Corp • Canon Inc. • Ushio Inc.
Equipment Suppliers	**LED packaging**	• Palomar Tech • Heller • Nordson ASYMTEK	• Besi	• ASM Pacific Tech • TOWA • Disco • Kulicke & Soffa (K&S)
Equipment Suppliers	**Luminaire assembly**	• Speedline Tech • Conveyor Tech	• ASM Siplace • Assembleon	• Panasonic • Fuji Machines • Nutek
Equipment Suppliers	**Test and inspection**	• KLA-Tencor • Cascade Microtech • Wentworth Labs • Orb Optronix • Lighting Sciences Inc. • Gamma Scientific • Radiant Zemax • SphereOptics • Daitron • Optest • Nanometrics • Chroma • Rudolph Tech • Labsphere	• Laytec • Bede • Bruker • Instrument Systems • Cameca • SUSS MicroTec • Ismeca	• Quatek • Fittech Co • QMC • Shibuya • Panasonic • Fujikom

Table 1.2 (continued)

	Supply Chain	North America		Europe	Asia		
Materials Suppliers	**Substrates**	• Rubicon • Silian • GT Advanced Tech • Cree • Kyma		• Monocrystal • Ammono • St. Gobain • Soitec	• Astek • STC • LG Siltron • Crystalwise Tech	• Air Water Inc. • TeraXtal • ProCrystal • Crystaland • Samsung	• Kyocera • Namiki • Mitsubishi Chem Corp • Hitachi Cable
	Chemical reagents	• SAFC Hitech • Dow Electronic Materials • Air Products	• SAES Pure Gas • Pall Corporation	• AkzoNobel • Linde Industrial Gases • Air Liquide	• Showa Denko KK • Matheson Tri Gas		
	Packaging	• Bergquist Company • Cambridge America • CofanUSA • Indium Corp.	• DuPont • Laird Tech / • Cookson Electronics	• Heraeus	• Chin-Poon • Gia Tzoong • HolyStone • Iteq • Leatec	• Polytronics Tech • TA-I Tech • Tong Hsing • Univacco Tech • Taiflex	• Viking Tech • Zhuhai Totking • Denka • Kyocera • NRK
	Phosphors/ Down-converters	• Intematix • Dow Electronic Materials • Philips Lumileds (internal) • GE (internal)	• Phosphortech • QD Vision • Nanosys • Pacific Light Tech	• Merck • Osram Opto Semiconductors (internal)	• Nichia (internal) • Mitsubishi Chemical Corp • Shin-Etsu • Denka		
	Encapsulation	• Momentive Performance Materials (InvisiSil)	• NuSil • Dow Corning	• Wacker Chemie (LUMISIL)	• Shin-Etsu		

The manufacturing of LED packages is a global activity but certain activities tend to be centered in certain geographical regions. The manufacture of LED epitaxial wafers involves sensitive intellectual property and is usually performed at the headquarters of the manufacturer, for example, by Philips Lumileds Lighting Company (PLLC) and Cree in North America, Osram Opto Semiconductors (Osram Opto) in Europe, and Nichia in Japan.

Some of the wafer processing is also handled locally but increasingly this is being transferred to wafer fab facilities located in Asia. Packaging of the LED die is often performed in China or Malaysia, usually in factories owned and operated by the parent company rather than by independent contract manufacturers. Currently, a significant portion of the packaging activity in Asia is not directly related to lighting. According to Strategies Unlimited, LED packaging for general illumination comprised 31% of global LED packaging revenues in 2013 ($4,470 million) and is expected to grow at a CAGR of 28% to become the dominant application by 2018, with a 58% share ($14,920 million) [6].

In North America, LED package manufacturers PLLC and Cree are both within the top seven worldwide by revenue and remain in the top tier with Nichia and Osram Opto when considering LED packages for general lighting applications [7]. Both companies manufacture their MOCVD epitaxial wafers in North America but much of the rest of the manufacturing process takes place through subsidiary companies located in Asia. PLLC has established a 150 mm wafer fab in Singapore with back-end processes performed in Penang, Malaysia. Cree has kept their 150 mm wafer fab in North Carolina; however, they have established package and test facilities in Huizhou, China, and Penang, Malaysia.

Another area of strength for North American companies is the production of tools and equipment for LED manufacturing and testing. The MOCVD crystal growth process for LEDs is the cornerstone of the entire LED manufacturing process. The world-wide market for MOCVD tools is dominated by two manufacturers: Veeco in North America and Aixtron in Europe. Both companies have benefitted from the growth of the LED market and continue to provide the vast majority of all MOCVD equipment used for LED production. North American manufacturers also provide a meaningful portion of the specialty wafer processing, packaging, and test and inspection tools required for LED production. Companies such as Plasma-Therm, Ultratech, and KLA-Tencor provide equipment to LED manufacturers all over the world.

Lamp and luminaire manufacturing is distributed worldwide. LED lamp manufacturing has sprouted up in North America, Europe, and Asia. Cree, Lighting Science Group, and Philips Lighting have developed LED lamp (bulb) manufacturing capabilities in North America. LED lamp manufacturing represents an opportunity for manufacturers to establish long-term domestic manufacturing capabilities to supply the North American market and export products. Similar to incandescent light bulb manufacturing, LED lamp manufacturing is likely to be highly automated with limited labor content. For luminaires local manufacturers have historically dominated production. This situation is likely to continue since LED luminaires are designed for local building types and luminaires can be bulky, leading to high shipping costs. Luminaire manufacturing is another opportunity for the development of long-term domestic manufacturing capabilities.

As the LED lighting market unfolds, there is also the likelihood that manufacturing capacity will be developed in regions where there is strong demand for the products. This minimizes shipping costs and considerations from the government may encourage local production.

1.2.2 OLED

The scale and location of OLED lighting production is not yet defined; however, Korean manufacturers LG Display and Samsung Display have made large commitments to developing OLED displays. LG Chem is using the experience gained in display manufacturing in the design and fabrication of lighting panels and has expanded their technology base through the acquisition of intellectual property from Eastman Kodak. In 2012 they completed the first manufacturing line designed for high-volume production, with an estimated capacity of 72,000 100 mm x 100 mm OLED panels per month. A similar production line is now being brought into production by First O-Lite in Nanjing, China. Several companies in Japan have upgraded their R&D lines for prototype production. These include Lumiotec, Kaneka, Konica Minolta, Panasonic, Pioneer, and Sumitomo Chemical. In Europe, Philips and Osram Opto have upgraded their pilot lines and have supplied many luminaire manufacturers with prototype products. In the U.S., OLEDWorks has begun production on their main fabrication line to complement an R&D line which they obtained from Eastman Kodak.

While most lines are producing rigid panels using batch processes, Konica Minolta has announced their construction of a roll-to-roll manufacturing facility at its Kofu Site in Yamanashi Prefecture, Japan. The planned capacity of the line will be about 1 million panels per month. Construction is scheduled for completion in the summer of 2014, with production beginning in the fall. The anticipated products include white panels of size 150 mm x 60 mm, with thickness of 35 µm and weight of 5 grams, and color-tunable panels of size 50 mm x 30 mm, thickness 0.29 µm, and weight of 0.6 grams. The panels will be formed on plastic substrates that can be bent with a radius of curvature of 10 mm.

The global extent of the whole supply chain can be assessed from Table 1.3 and Table 1.4. These lists are incomplete, however, and some of these companies are still at the development stage and may not yet have commercial offerings.

Table 1.3 The OLED Supply Chain: Global Equipment and Materials Suppliers

	Supply Chain	North America	Europe	Asia
Equipment Suppliers	**Vapor deposition**	• Applied Materials • Kurt Lesker • Trovato Mfg	• Aixtron • Beneq • Cambridge Nanotech	• Canon Tokki • GJM • Hitachi Zosen • Jusung • SFA • SNU • Sunic • Ulvac
Equipment Suppliers	**Coaters and printers**	• Dimatix • Kateeva • Novacentric • nTact • Xenon Corp.	• Coatema • Roth & Rau	• Dai Nippon Screen • Seiko Epson • Sung Am Machinery • Tazmo • Tokyo Electron • Unijet
Equipment Suppliers	**Encapsulation**	• Coherent • Veeco	• MBraun • Oxford Lasers	• Avaco • Wonik IPS • YAS • Canon Tokki • Ulvac
Equipment Suppliers	**Test and inspection**	• Colnatec • Radiant Zemax	• Laytec	
Materials Suppliers	**Substrates**	• Alcoa • DuPont-Teijin • Guardian • Corning • PPG • Pilkington	• ArcelorMittal • St. Gobain • Schott Glass	• Asahi Glass • LG Chem • Nippon Electric Glass • Samsung-Corning
Materials Suppliers	**Extraction Materials**	• 3M • Pixelligent	• Novaled	
Materials Suppliers	**Active organic materials**	• DuPont • Plextronics • PPG • UDC	• BASF • Cynora • Merck • Novaled • Solvay	• Aglaia • Samsung SDI • Daejoo • Doosan • Dow Electro-Materials • Duksan Hi-Metal • Hodogaya • Idemitsu Kosan • Jilin Optical • JNC/Chisso • LG Chem • Lumtech • eRay Opto • Mitsubishi Chemical • Mitsui Chemical • Nippon Steel Sumikin • Nissan Chemical • RuiYuan • Sumitomo Chemical
Materials Suppliers	**Conductors**	• Cambrios • DuPont • Intrinsiq Materials	• Agfa • Heraeus • St. Gobain	
Materials Suppliers	**Encapsulation**	• DuPont • 3M • UDC •	• Delo • Henkel • SAES Getters • Sud-Chemie	• Samsung SDI • Dynic Tera-Barrier Films

Table 1.4 The OLED Supply Chain: Global Panel and Luminaire Producers

Supply Chain	North America	Europe	Asia		
Panels	• OLEDWorks	• Astron-Fiamm • Osram Opto • Philips • Fraunhofer COMEDD	• First O-Lite • Kaneka • Konica Minolta • Lumiotec • Mitsubishi Chemical	• NewView • Nippon Seiki • Panasonic-Idemitsu (PIOL) • Pioneer • Showa Denko	• Sumitomo Chemical • Toshiba • Visionox • LG Chem • Mitsubishi Pioneer (MPOL)
Luminaires	• Acuity • WAC Lighting • Blackjack Lighting • Alkilu • LiteControl	• Blackbody • Liternity • Osram Opto • Philips • Tridonic	• Hanyoung • KwangMyung Lighting • Mitsubishi-Pioneer • NEC Lighting	• Verbatim • Visionox • Synqroa • Intelas	

The manufacturing of active OLED materials is spread across three continents and substantial new investments are being made in the required facilities, to serve both display and lighting applications. Major producers include DuPont and PPG in North America, BASF and Merck in Germany, Idemitsu Kosan and Sumation in Japan, and Dow Chemical and Duksan Hi-Metal in Korea. There are experienced equipment makers in these same four countries. However, the large capital investment required to make the deposition equipment for display applications and the uncertain size of the market for OLED lighting are causing apprehension amongst tool makers. The market for small-scale equipment suitable for R&D operations is still healthy and is being pursued successfully by North American manufacturers, such as Kurt J. Lesker Company and Trovato Manufacturing.

1.3 The U.S. Department of Energy (DOE) SSL Program

In the United States, lighting consumed about 18% of the total site electricity use in 2010, according to a recent DOE report [8]. A second DOE report also finds that SSL technology offers the potential to save 217 terawatt-hours (TWh), or about one-third of lighting site electricity consumption, by 2025 [9]. That savings in site consumption corresponds to about 2.5 quadrillion British thermal units (quads) of primary energy, which is approximately equal to the forecasted 2025 energy production from "other" renewable sources such as wind and solar combined, making SSL a significant contributor to energy supply issues by reducing the demand on energy resources.

1.3.1 Program Elements

DOE has responded to this opportunity with the Solid State Lighting Program, providing direction and coordination of many efforts intended to advance the technology and to promote adoption.[b] The DOE supports SSL technical advancement through three tightly integrated program elements: Competitive R&D, Market-based Technology Advancement efforts such as laboratory testing and field demonstrations, and Market Engagement with researchers, manufacturers, utilities, lighting users, and others. Feedback loops among the elements induce technology improvements more quickly than would otherwise occur.

DOE's program addresses two overarching objectives:
- Overcoming technical and design barriers to efficient, high quality solid state lighting, and
- Establishing the foundations for successful market introduction

The DOE SSL Program recognizes that energy savings come from the development and widespread adoption of energy-efficient lighting technology. To address the development of energy-efficient lighting technology, the DOE has supported “Core Technology Research” and “Product Development” R&D in solid-state lighting. In addition, DOE supports basic research through the Office of Science and their Energy Frontier Research Centers (EFRCs), and both play a role in developing the new scientific concepts that can be applied to solid-state lighting.

[b] For more information, go to http://energy.gov/eere/ssl/about-solid-state-lighting-program.

Core Technology Research is the application of new scientific concepts to SSL technology to improve efficiency or lighting performance, such as the development of quantum dot down-converters or exploring the source of current density droop.

Product Development describes the development of advanced, breakthrough products that can be either luminaires or subcomponents in the manufacturing supply chain. A good example of a Product Development project that DOE has supported was the development of the hybrid luminaire concept by Philips Color Kinetics. This product used cool white emitting LEDs together with red emitting LEDs to provide warm, white light with excellent color rendering.

Manufacturing R&D focuses on research to improve the state of manufacturing for LED and OLED-based solid-state lighting products in order to reduce cost and improve quality. There have been projects to improve the MOCVD epitaxial tools, develop wafer inspection equipment, improve phosphor deposition processes, and several more. The DOE SSL Program recognizes the need to address the primary technological barriers to the adoption of SSL products – manufacturing cost and product consistency. To address these issues, DOE provides support for SSL Manufacturing R&D, which has the additional aim of creating and retaining manufacturing jobs in the U.S. The DOE SSL Manufacturing R&D effort is the topic of this document, the DOE SSL Manufacturing Roadmap.

The portion of the DOE SSL Program addressing Core Technology Research and Product Development is described in the annually updated DOE SSL R&D Multi-Year Program Plan (MYPP). Market-based Technology Advancement—including laboratory testing, quality reporting, field demonstrations, technical education, competitions, and more—are described in the DOE SSL Market-based Technology Advancement Multi-Year Plan.

Together, the MYPP, Market-Based Technology Advancement Multi-Year Plan, and Manufacturing Roadmap describe the breadth of activities that the DOE SSL Program undertakes to achieve the basic DOE mission of energy savings. For R&D, DOE supports a continuum of research from Basic Research (supported by the DOE Office of Science) to Core Technology Research, Product Development, and Manufacturing R&D. This R&D has not just supported the development of highly efficient light sources, but has supported advancements in cost and quality that have enabled SSL products to rapidly enter the lighting market and save significant amounts of energy. In addition, the SSL Market-Based Technology Advancement Activities have helped promote consumer confidence in SSL technology and minimize the likelihood that the SSL market will repeat mistakes that greatly delayed CFL market entry. Impartial, trusted analysis from laboratory testing and field demonstrations helps to identify and intercept technology problems early on, alerting manufacturers to needed improvements and helping to put detailed information into the hands of buyers.

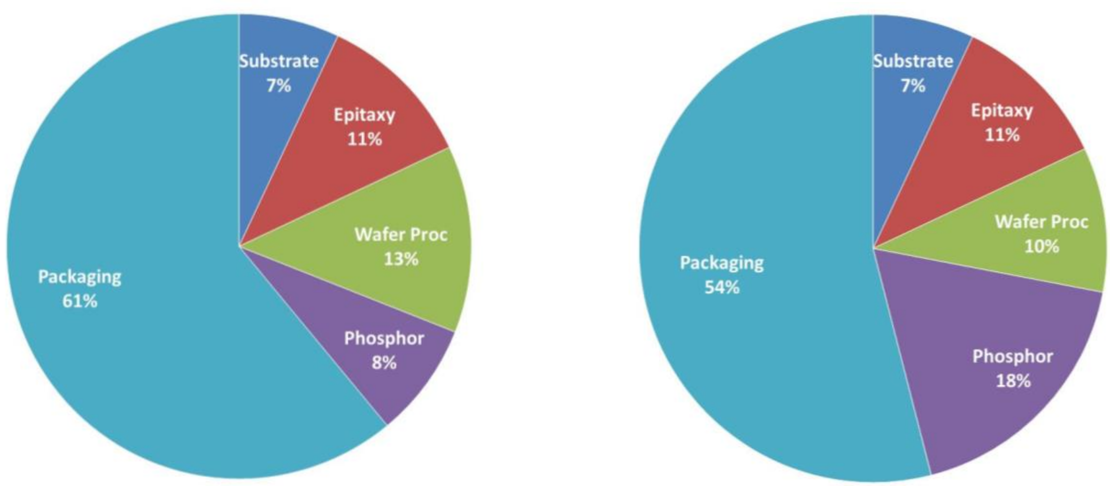
1.3.2 Cost Drivers

For SSL manufacturing, reducing the cost of the final product involves an understanding of the source of costs at each key stage in the manufacturing process, and requires careful attention to the design of the product and of the manufacturing process.

LED Cost Drivers

The typical cost breakdown for a high-power and mid-power LED package is shown in Figure 1.5 below. The data for a high-power package assumes high-volume manufacturing of 1 mm^2 die on 100 mm diameter sapphire substrates and packaging of the die in ceramic packages to produce warm white phosphor-converted LED lighting sources. The data for a medium-power, warm white phosphor-converted LED package assumes a 0.25 mm^2 die packaged in a plastic leaded chip carrier (PLCC) package of similar dimensions. The high-power package has until recently been the mainstay of the lighting market; however, high-performance, medium-power devices have emerged as a realistic alternative due in part to their lower cost. In both cases, the analysis was performed using the LEDCOM modular cost model [10]. In this model, the yield for each process step defines the cost of that step and a cumulative overall wafer yield is calculated after each step to reflect the percentage of good product progressing to the next step or, in the case of the final step, the percentage of good product produced.

The cost breakdown for the high-power LED package is largely unchanged compared with 2013, although there is an overall cost reduction of around 14%, which is largely associated with reductions in raw materials costs and yield improvements. The die cost and package cost are much lower for the mid-power package, although the phosphor is still applied over a similar area; hence, its relative importance to the overall cost increases. Typically, the mid-power package cost will be 5 to 10 times lower, depending on die area, and is reflected in a similar price differential.



High-Power LED Package *Mid-Power LED Package*

Figure 1.5 Typical Cost Breakdowns for High-Power and Mid-Power LED Packages
Source: LEDCOM model with inputs from DOE SSL Roundtable and Workshop attendees

Figure 1.5 indicates that a significant proportion of the cost remains concentrated in the die-level packaging stage. This result is not too surprising since the final product is a packaged die and there are many thousands of such die on each wafer (e.g., around 5,000 1 mm^2 die on a 100 mm diameter substrate). Therefore, costs associated with die-level activities will tend to dominate and manufacturers will need to address die-level packaging processes or perform more of the packaging activities at a wafer level in order to realize the required cost reductions. Figure 1.6 shows how the high-power LED package cost elements may change over time as volumes continue to ramp, falling to about 32% of 2014 values by 2020. The overall reduction in cost over this time period remains consistent with the price projections reported in the 2014 MYPP assuming general reductions in materials costs, a movement toward chip-scale packaging, and a continuing erosion of gross margins [5]. However, this simple analysis does not reflect a growing trend toward specialization of package types to match specific lighting applications, which facilitate performance optimization and cost reduction at the luminaire level.

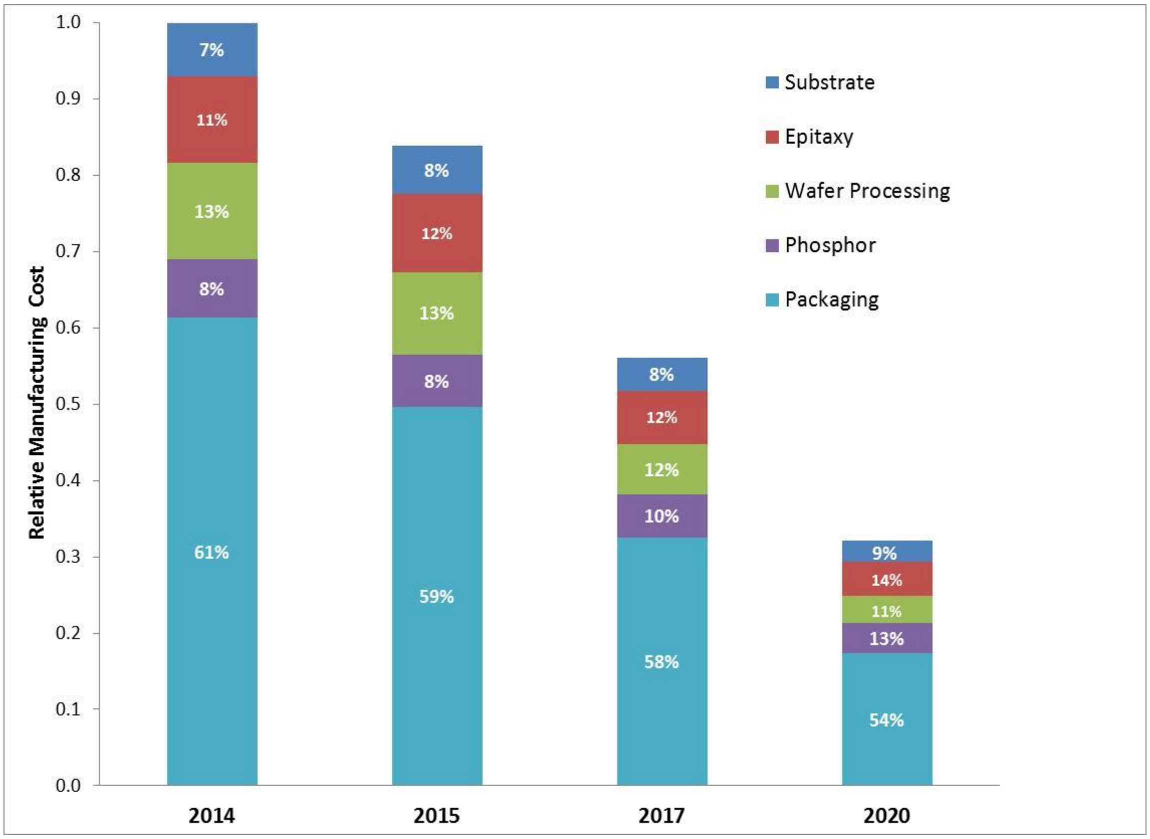


Figure 1.6 Projected LED Package Cost Reduction

Source: LEDCOM model with inputs from DOE SSL Roundtable and Workshop attendees

There is plenty of room for innovation in this area and DOE anticipates many different approaches to cost reduction, including the following:

- Increased equipment throughput
- Increased automation
- Improved testing and inspection
- Improved upstream process control[c]
- Improved binning yield
- Optimized packages (e.g., simplified designs, lower cost materials, and multi-chips)

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[c] Wafer-level costs such as substrates, epitaxial growth, and wafer processing, comprise a smaller percentage of the final device cost, but improvements here can have a significant impact on packaging costs and device performance (see Section 2.3).

- Higher levels of component integration (hybrid or monolithic)
- Chip-scale and wafer-scale packaging

The typical cost breakdown for a lamp or luminaire will vary depending on the application. Figure 1.7 shows a comparison of the cost breakdown for an outdoor area lamp, indoor downlight, and A19 replacement lamp. The cost breakdowns are not expected to have changed significantly over the past year. It is apparent that the relative costs for different form factors can vary considerably, especially the cost of the LED package(s). Overhead costs also represent a significant cost element and should be included in the cost charts along with the bill of materials.

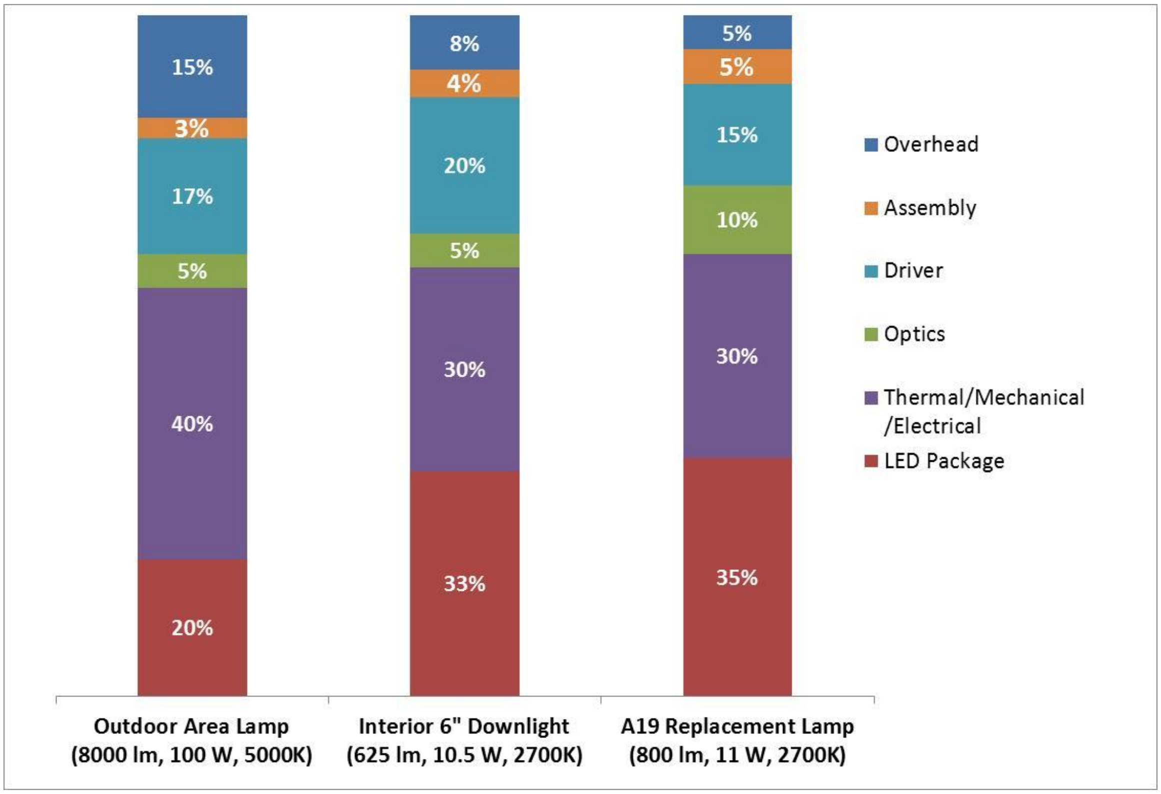


Figure 1.7 Comparison of Cost Breakdown for Different Lighting Applications
Source: DOE SSL Roundtable and Workshop attendees

The overhead included in the cost charts refers to manufacturing engineering, product development, documentation, packaging, in-line and compliance testing, shipping, and distribution. The retail price will include an additional sales margin of maybe 30 to 50%.

For a specific product, it is instructive to consider how the cost breakdown might change as a function of time. Figure 1.8 shows how the relative manufacturing cost for a common A19 60 W equivalent replacement lamp is expected to change between 2014 and 2020. The major change in the cost breakdown relates to the cost of the LED package, which is anticipated to fall from around 35% of the lamp cost in 2014 to around 22% by 2020. As noted above and shown in Figure 1.7, relative costs vary widely among specific luminaire and lamp types, so it is not possible to project a generic luminaire cost breakdown. Nonetheless, for most types, a factor of two to three times reduction in relative cost is not an unrealistic expectation.

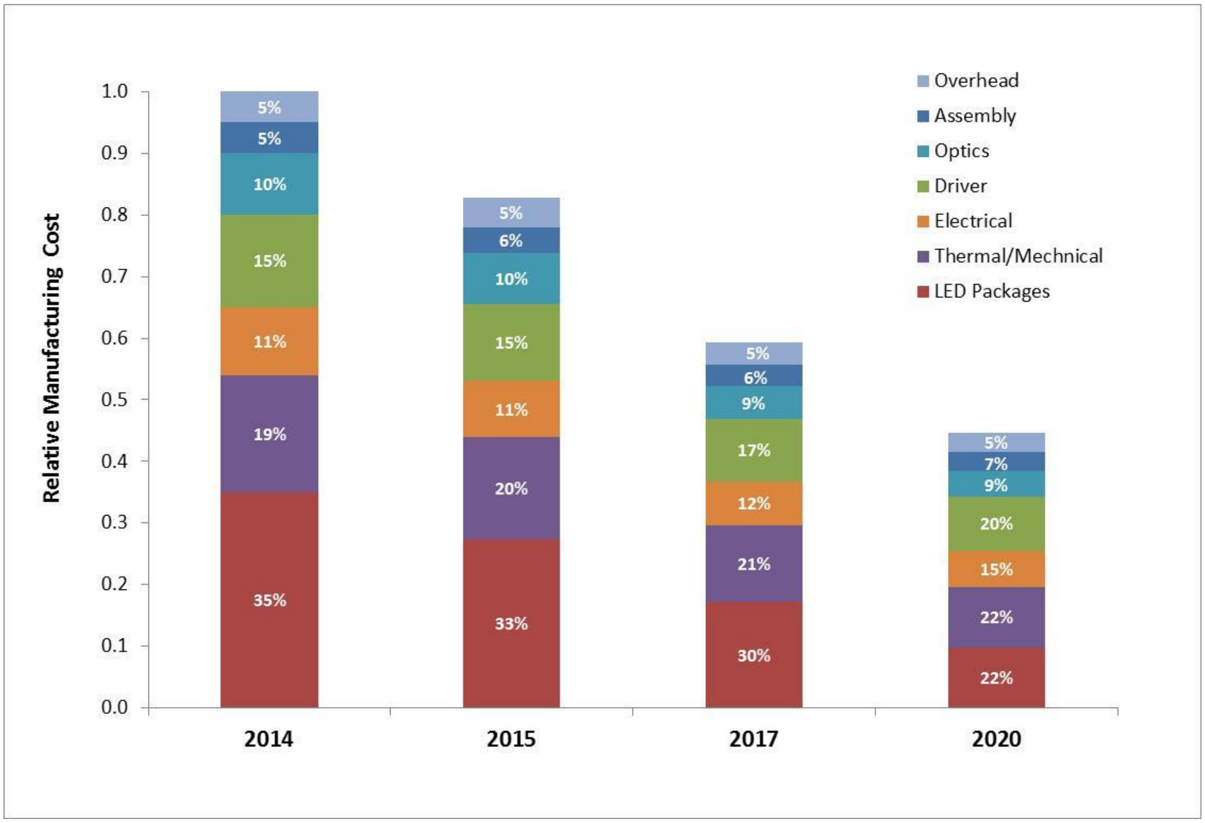


Figure 1.8 Cost Breakdown Projection for a Typical A19 Replacement Lamp
Source: DOE SSL Roundtable and Workshop attendees

While early on the cost of LED packages dominated the total lamp cost, as time has progressed, this has become less the case. We are now approaching a stage in which no single cost element will dominate, and cost reduction will be achieved by focusing on optimization of the complete system rather than focusing on any specific cost element.

The key cost drivers for each major element of the LED supply chain are summarized in Table 1.5.

Table 1.5 The LED Supply Chain: Key Cost Drivers

Supply Chain		Cost Drivers		
Equipment Suppliers	Epitaxial growth	• Uniformity • Throughput	• Reagent usage efficiency	• In-situ monitoring/ Process control
	Wafer processing	• Throughput	• Automation	• Yield
	LED packaging	• Throughput	• Flexibility (packaging materials and package types)	
	Luminaire assembly	• Throughput	• Automation	• Chip scale packaging
	Test and inspection	• Throughput	• Accuracy	• Reproducibility
Materials Suppliers	Substrates	• Diameter	• Quality	• Standardization
	Chemical reagents	• Quality/Purity	• Bulk delivery systems	• In-line purification
	Packaging	• Standardization	• Plastic Packages	• Package Shrinks
	Phosphor	• Quality/Efficiency • Consistency	• Stability (thermal and optical flux)	• Reliability
	Encapsulation	• Quality	• Reliability	• Stability (thermal and optical flux)
Die Manufacturing		• In-line inspection/ Process Control	• Yield • Testing	• Throughput • Capital costs
Package Manufacturing		• Modularization • In-line inspection/ Process control	• Labor content • Testing • Standardization	• Yield • Throughput
Luminaire Manufacturing		• Automation/Labor content • In-line inspection/ Process control	• Testing (performance and compliance)	• Modularization • Throughput

OLED Cost Drivers

With respect to OLED lighting, cost reduction remains the highest priority and greatest challenge. Since production of lighting panels has been so limited, it is useful to look at the experience with OLED panels for display applications.

There has been very rapid growth in the scale of OLED manufacturing for displays over the past few years, with annual production rising to over one million square meters in 2012. However, most of the production has been by one company (Samsung) for one product type – the display in a smart phone. These are high-value products and the manufacturing cost of a small 5" panel is roughly \$25 (\$4,000/m^2).The success of Samsung in making profits while selling phones with OLED displays has led other Asian companies to invest heavily in OLED manufacturing, leading to total capital investments of in excess of \$10 billion per year. However, repeating this success with other products presents considerable challenges, mainly concerning cost rather than performance. For example, DisplaySearch estimates that the manufacturing cost of the OLED panel in a 55" TV, as produced by LG Display, is around \$3,600 (\$4,500/m^2).

The production of OLED panels for lighting has mostly been accomplished in lines with much less automation, leading to even higher costs per area. The prices charged by panel manufacturers have been \$5,000/m^2 or more, leading to luminaire prices in excess of \$10,000/m^2 or \$1,000/klm. In a realization that such prices are too high to drive significant market adoption, LG Chem has announced that their panel prices for luminaire manufacturers will be reduced to about \$200/klm from an average of \$600/klm.

Substantial cost reduction will be needed for commercial success in OLED TV and OLED lighting markets. Since 55" LCD TVs illuminated by LED backlights can now be purchased at retail for below \$800, broad market penetration of OLED TVs will require manufacturing costs for OLED panels to be around \$250/m^2. If this were achieved, the corresponding cost for OLED lighting panels with a luminous emittance of 10,000 lm/m^2 would be near \$25/klm. The long-term target of the DOE SSL Program for OLED panels is \$10/klm.

Therefore, the cost of OLED TVs needs to be reduced by a factor of 15, and that of OLED lighting by 30, based on the estimates shown in Table 1.6. This has led to vigorous debate within the community about the level of synergy between these two applications. Some proponents of OLED lighting argue that the best way to reach the long-term cost targets is to leverage the advances that will come from the development of OLED televisions. Others believe that costs of approximately \$10/klm cannot be reached via this route, and that radically different methods are needed that will result in reductions on a shorter time scale. The two applications have different performance requirements and economics that can affect the choice of manufacturing approaches. Lighting requires much lower cost, higher efficacy, and longer lifetime to be competitive, so while a manufacturing approach may be suitable for displays it may not entirely cross over to lighting.

Some important factors for reducing the cost of manufacturing of OLED panels for televisions will also help to reduce costs for lighting. These include the following:

- Cost of organic materials
- Material utilization
- Production yield
- Desiccant-free encapsulation

Additional cost reductions needed are more specific to lighting:

- Avoiding the use of photolithography
- Short process times,
- Inexpensive substrate and cover
- Formation of light extraction enhancement layers

Formation of the thin-film transistor (TFT) backplane and patterning of sub-pixels are not relevant for lighting.

The cost of OLED panels can be broken down into three major segments—the integrated substrate, organic stack, and assembly, which includes encapsulation and testing. To avoid the commitment of large amounts of capital on a high-risk venture, the contribution of each segment must be reduced substantially before large production lines are installed. The schedule for cost reduction, displayed in Table 1.6, is based upon presentations made by LG Chem, Philips, Moser Baer, and OLEDWorks, and input from the DOE SSL Workshops. The costs for the three segments are estimated for each constructed panel, including equipment depreciation, but are not adjusted for the yield of good panels. That factor is taken into account in the final row. The overhead cost includes manufacturing engineering, insurance, property taxes, product development, documentation, packaging, shipping, and distribution.

Table 1.6 OLED Panel Cost Estimated Progress ($/m^2)

	2013	2014	2016	2020	2025
Integrated Substrate	250	200	150	40	20
Organic Deposition	600	500	250	70	30
Assembly and Test	350	300	200	50	20
Overhead[d]	300	200	100	20	10
Total (unyielded)	1,500	1,200	700	180	80
Yield of Good Product (%)	25	40	70	75	80
Total Cost	6,000	3,000	1,000	240	100

[d] See Section 1.3.2 for a list of overhead costs included.

Note that the estimates in Table 1.6 represent industry averages. The division of costs between segments may vary substantially between companies, depending for example, on the number of organic layers or the complexity of the extraction enhancement structures.

Since luminaire production has been confined mainly to samples and demonstrations, it is still too early to forecast the evolution of luminaire costs in high volume. The total cost of the luminaire is expected to be roughly twice that of the panel for purely functional lighting, but may be higher for decorative fixtures.

The key cost drivers for each major element of the OLED supply chain are summarized in Table 1.7.

Table 1.7 The OLED Supply Chain: Key Cost Drivers

Supply Chain		Cost Drivers
Equipment Suppliers	Sealing	• Seal integrity • Process time
	Evaporators	• Deposition rate • Materials utilization • Capital cost
	Wet Coaters	• Drying time • Patterning
	Luminaire Assembly	• Modularization • Automation
	Test & Inspection	• Throughput • Accuracy
Materials Suppliers	Substrates	• Material selection • Surface condition
	Organic Stack	• Sales volume • Efficacy • Lifetime
	Encapsulation	• Increased sales volume • Elimination of desiccants
	Electrodes	• Material selection • Patterning
	Extraction Structures	• Processing yield • Performance
Panel Manufacturing		• Yield • Throughput • Capital • Testing
Luminaire Manufacturing		• Panel price • Labor • Modularization • Testing

2 LED PACKAGE AND LUMINAIRE ROADMAP

The LED luminaire manufacturing supply chain is shown schematically in Figure 1.1. The main manufacturing flow comprises LED die manufacturing followed by LED package manufacturing, leading to luminaire manufacturing. Various inputs are required to fuel the manufacturing, ranging from LED manufacturing equipment through specialty materials to test and measurement equipment. Each element of the supply chain is described in more detail in the following sections, along with an indication of the major participants and their geographical distribution.

2.1 LED Manufacturing Equipment

The production of LED packages and luminaires involves the use of a wide range of specialized manufacturing equipment. The critical equipment requirements for each major manufacturing step are discussed in the following sections, along with some consideration of the worldwide equipment manufacturing base.

LED wafer fabrication facilities are located throughout the world. Semiconductor Equipment and Materials International (SEMI) produces a quarterly "Opto/LED Fab Forecast" that provides information on capacities and projected construction and equipment spending for the next 18 months [11]. The analysis covers all LED fab activity and not just LEDs manufactured for SSL. The 2014 forecast anticipates a stabilization of equipment spending following significant declines during 2013, and projects a 60% increase in overall fab construction spending. Overall, it is forecast that these investments will increase the installed capacity for LED manufacturing by about 12% in 2014 and 14% in 2015 [11].

The manufacturing equipment landscape is continually evolving in order to satisfy the ever-changing demands of the LED and luminaire manufacturers. Many manufacturers place a premium on low acquisition cost and have in the past tended to modify their own equipment. More recently, the communication between equipment manufacturers and end users has improved; the market better understands the requirements of the LED manufacturing industry, and has begun to offer a more complete range of manufacturing equipment specifically designed to meet those needs.

Successful equipment is most often characterized by a low cost of ownership (COO). COO is the total cost of producing a good part from a piece of equipment (see Section 2.6.1) and can be used to drive manufacturing equipment evolution to reduce the cost of production. To achieve a low COO, the equipment must offer excellent repeatability and reproducibility leading to high process yields, low acquisition and operating costs, high throughput, and high utilization. In general, the Roundtable and Workshop participants anticipate a factor of two reduction in COO over a five-year time scale.

2.1.1 Epitaxial Growth Equipment

Epitaxial growth is of fundamental importance in the manufacturing process and is currently accomplished using MOCVD. MOCVD is the only technology capable of growing the entire device structure in a cost-effective manner, including the complex low-temperature nucleation layer, the thick GaN buffer, the multi-quantum well (MQW) active region, and p-GaN cap. The focus therefore remains on developing improved MOCVD growth equipment such as the Veeco MaxBright platform shown in Figure 2.1, which was developed with R&D funds from the Program [12]. Alternative growth methods such as hydride vapor phase epitaxy (HVPE) and physical vapor deposition (PVD) offer advantages over MOCVD in some limited areas of application but have not gained traction in the manufacturing process. HVPE is able to deposit thick GaN layers at high growth rate and low cost, and is commonly used to produce GaN templates. PVD is currently being investigated as a low-cost method for depositing an AlN nucleation layer on sapphire and silicon substrates.

Figure 2.1 Veeco MaxBright MOCVD System
Source: Veeco Instruments, Inc.

The main issues driving MOCVD epitaxial growth equipment development are as follows:

- Wavelength uniformity and reproducibility
  Achieving tighter control over the wavelength uniformity and reproducibility of the LED light emission is critical in order to improve color point consistency in the final product, optimize product yields, eliminate the need for binning, and reduce product costs. Similarly, the equipment must enable continuous improvement in material quality and internal quantum efficiency (IQE) in order to achieve the target efficacy improvements. Both requirements will be met by improved equipment design, process optimization, and process control. One area where significant progress has been made at the equipment level is in monitoring and controlling the wafer bow. Wafer bow is caused by stresses during growth and creates non-uniform contact between the wafer and the carrier, which results in non-uniform heating. The indium gallium nitride (InGaN) MQW active region composition is extremely sensitive to temperature, resulting in non-uniform wavelength emission. One elegant solution has been to create an advanced engineered wafer carrier where the shape of the pockets match the wafer bow at this critical stage in the growth process and provide uniform heating of the wafer. Wavelength uniformity can be significantly improved using this technique, with the proportion of the wafer falling within a 5 nm bin, rising from 73% to over 90% as reported previously by Veeco [13].

- Throughput (cycle and growth times)
  Large-capacity manufacturing equipment (typically up to 56 x 2”, 14 x 100 mm, 6 x 150 mm or 3 x 200 mm wafer capacity) capable of producing high-quality material is readily available, and developments in cluster tool technology offer the prospect of even higher throughputs and corresponding reductions in COO. An example of the Veeco MaxBright 14 x 100 mm wafer carrier is shown in Figure 2.2. Equipment design modifications and process improvements have allowed the GaN growth rate to reach 15-20 μm/hr, which essentially eliminates growth time issues for the thicker GaN layers. Nevertheless, there remains a need to continue to improve equipment capacity and reduce growth cycles in order to lower the overall COO.

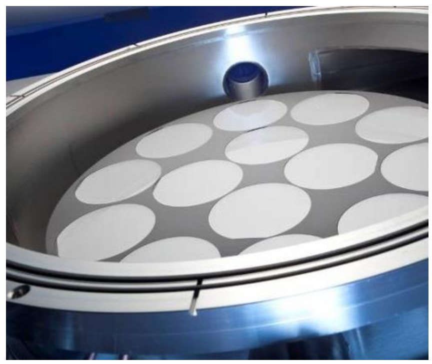


Figure 2.2 Veeco MaxBright™ 14 x 100 mm Wafer Carrier
Source: Veeco Instruments, Inc.

- In-situ monitoring and process control
  The demanding reproducibility and uniformity requirements suggest the need for advanced process control measures in conjunction with sophisticated in-situ monitoring (especially wafer temperature) and accurate process modeling. Active temperature control at the wafer surface is of particular importance since temperature drives the growth process. Developments in the use of ultraviolet (UV) pyrometry to measure temperatures at the wafer surface rather than remotely via the carrier surface offer a more direct route to active control. Other in-situ tools, such as for monitoring wafer bow, are routinely incorporated into most production reactors, although they are not generally used in active monitoring and control of the manufacturing process.

- Reagent usage
  High-purity metalorganic alkyl sources and hydride gases are expensive. One of the major costs for the epitaxially grown wafer is associated with trimethylgallium (TMG), since a large amount of the material is used to produce an LED epitaxial structure. This is due to a usage efficiency of only 20-25%. Work is required at the equipment design level to improve the source efficiencies and reduce manufacturing costs.

A reduced COO might be achieved in many different ways, such as increased throughput (reduced cycle times and/or increased capacity), lower capital cost, improved materials usage efficiency, smaller footprint, or increased yield. Process control improvements will increase yield, and equipment design changes will increase the efficiency of reagent usage. Finally, overall equipment efficiency (OEE) improvements will reduce operating costs through improved preventive maintenance schedules, minimization of non-productive operations such as chamber cleaning, and introduction of high throughput multi-chamber cluster configurations. Although it is difficult to specify at this stage which approaches will be the most effective, all such actions will reduce the COO.

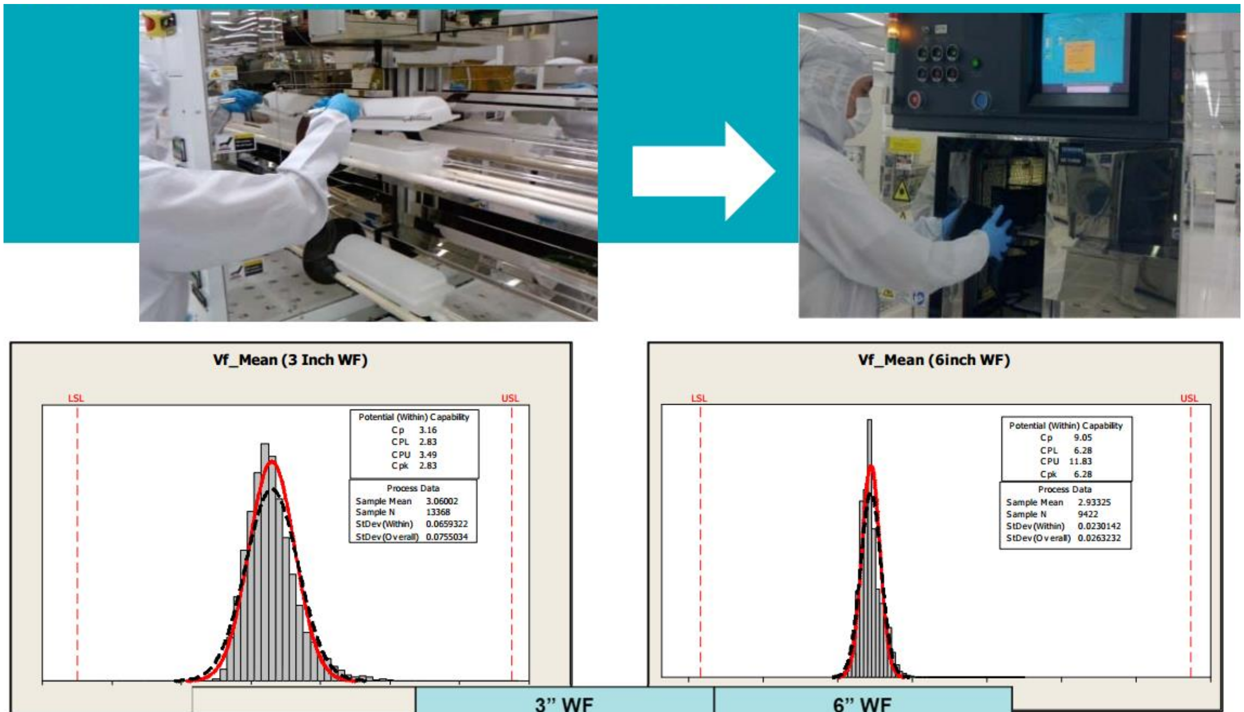
The MOCVD equipment market is dominated by two companies: Veeco Instruments in North America and Aixtron in Europe. Between them they provide around 90% of the MOCVD equipment used for the manufacturing of GaN-based LEDs. The only other significant MOCVD equipment manufacturer is Taiyo Nippon Sanso in Japan, who operate almost exclusively within their home market.

2.1.2 Wafer Processing Equipment

The wafer processing equipment used to fabricate LED devices on the MOCVD-grown semiconductor wafers is largely derived from equipment originally developed for the silicon and GaAs wafer processing industry. Earlier problems associated with the lack of suitable manufacturing equipment for wafer processing have receded to some extent. Partly this is due to a general migration toward larger substrate diameters that are more compatible with modern equipment, but also to the fact that equipment manufacturers have responded to the growing demand and introduced more flexible platforms to cope with the wide mix of substrate types and diameters. A good example is the Ultratech Sapphire 100 lithography tool shown in Figure 2.3, which allows for quick wafer size change between 2”, 75 mm, 100 mm, and 150 mm for both sapphire and SiC substrates.

In the past couple of years, the larger industrial players such as Philips Lumileds, Cree, and Samsung have moved their production lines to 150 mm wafers and have been able to benefit from the availability of more modern processing equipment with an improved process capability. For example, Philips Lumileds reported a factor of two improvement in process capability (Cpk) for wafer annealing when moving from 75 mm to 150 mm wafers due to the availability of a vertical furnace with larger flat zone (see Figure 2.4) [14].

Figure 2.3 Ultratech Sapphire 100 Stepper for LED Manufacturing
Source: Ultratech, Inc.



	3” WF		6” WF	
Parameters	Average	Stdev	Average	Stdev
Vf_Mean (350mA)	3.06	0.075	2.93	0.026

Figure 2.4 Improved Process Control Using Modern 150 mm Processing Equipment
Source: Iain Black, Philips Lumileds, SSL Manufacturing Workshop, Boston, MA, June 2013

Equipment companies such as Plasma-Therm (North America) and Oxford Instruments Plasma Technology (Europe) offer equipment for dry processing (plasma deposition, plasma etching, and reactive ion etching), including processes specifically developed for GaN-based materials. Companies such as Ultratech (North America) and Karl Suss (Europe) have addressed the lithographic needs of the industry, while companies such as EV Group (Europe) and JPSA (North America) have produced more specialized equipment for processes, including wafer bonding/de-bonding, laser lift-off (LLO), and wafer ablation and scribing. Temescal (North America) and others provide metallization equipment. North American companies are well represented in the supply of wafer processing equipment.

2.1.3 LED Packaging Equipment

LED die are generally mounted in a package in order to provide an effective interface between the small semiconductor die and the rest of the system. The package provides good thermal conductivity, control over the light distribution, and electrical connectivity. Various types of packaging equipment will be employed depending on the die configuration (top or bottom emitting) and design of package. For example, die attach equipment might be required to perform flip-chip processing and eutectic bonding onto ceramic carriers or silicon sub-mounts. Electrical connections between the semiconductor die and the sub-mount or package can be made using wire-bonding equipment or solder bump technology equipment. Encapsulation and/or phosphor material is often conformally coated over the surface of the die once it is mounted on the sub-mount or ceramic substrate. Finally, a lens is generally molded or attached above the LED die to provide the required light distribution pattern. A recent development has been the introduction of mid-power LED packages for the lighting market based on low-cost plastic leaded chip carriers (PLCC). Such packages have more standardized form factors and are used extensively in the backlighting industry. Performance improvements have seen them being applied to lighting applications, especially where a diffuse source is required. Hence, the manufacturing of LED packages will involve the application of a range of types of packaging equipment to cover a range of technologies, processes, and package designs.

One consequence of an increasingly diverse range of package designs is the need to achieve a high degree of flexibility in the manufacturing line to handle the different options. For example, the packaging line is required to handle different package shapes and materials, different die sizes, different die attach methods, different phosphor application approaches, and different optics. Establishing completely separate packaging lines for each different design is not practical; hence, the ability to flexibly reconfigure the line for different batches of packages is essential.

In a general sense, the packaging of electronic and optoelectronic components is a well-established technology. Conventional semiconductor packaging equipment already exists and is well suited to the task with a fairly limited requirement for customization. Companies such as ASM Pacific Technologies in Asia, Besi in Europe, and Palomar Technologies in North America provide die attach, wire bonding, and flip-chip bonding equipment. Companies such as Nordson ASYMTEK in North America provide dispensing equipment (e.g., phosphor coating, silicone encapsulation, epoxy dispensing, lens attachment, and flip-chip).

A certain amount of automation is employed; however, the need for a high degree of process flexibility and the ability to handle a wide range of product types on the same production line means that LED die packaging remains a labor-intensive activity. Consequently, much of the packaging activity takes place in regions with lower labor and tooling costs such as Asia. Shipping costs for small and light LED packages are insignificant, also contributing to the decision to manufacture such products at off-shore facilities.

If one considers the explosion in package designs and the need for multiple bins for each package design, then this culminates in the need to handle a massive number of stock-keeping units (SKUs). Such a high number of SKUs creates a whole new set of logistical problems beyond the basic manufacturing complications.

2.1.4 Luminaire and Module Assembly Equipment

Assembly equipment for SSL modules and luminaires is largely the same as that for general electronic modules. The process first involves manufacturing the various sub-assemblies such as the driver, the light engine, the core thermal and mechanical components, and the optics. Lastly, the final assembly, which is currently fairly labor intensive, involves combining these sub-assemblies mechanically and electrically.

A key element of the LED-based luminaire and module assembly process is the use of surface-mount technology (SMT) manufacturing equipment to mount one or more LED packages onto a printed circuit board (PCB) to create the light source. Suppliers of PCB and stencil-printing manufacturing equipment include Speedline Technologies in North America and Nutek in Asia. Suppliers of SMT manufacturing equipment include SMT Manufacturing, Inc., in North America; ASM Siplace and Assembleon in Europe; and Panasonic and Fuji Machines in Asia.

There have been moves to automate elements of the manufacturing operation in order to improve efficiency and reduce costs; however, a typical current manufacturing operation still involves a mixture of automation and manual assembly.

2.1.5 Test and Inspection Equipment

Test and inspection equipment is required throughput the LED package manufacturing process, from the inspection and qualification of incoming materials, through process monitoring and control, to end-of-line product testing.

Test and inspection equipment for LED die manufacturing starts with qualification of manufacturing materials. This involves non-destructive optical inspection of substrates using something like the KLA-Tencor Candela 8620 Inspection System, which was developed with R&D funds from the Program [15]. Often this test is performed as part of an incoming quality inspection by the epitaxial wafer manufacturing unit; however, increasingly, the burden of measurement will fall to the substrate manufacturer. Such inspection tools are also used throughout the wafer manufacturing process to detect killer defects at an early stage and optimize process yields.

Another critical testing area for LED die manufacturing is high-speed testing of the final LED package. The ability to rapidly characterize and bin LED packages based on lumen output, color coordinate (correlated color temperature [CCT] and color rendering index [CRI]), and forward voltage, is an important requirement. In the past, such measurements have been performed at room temperature (25°C), but increasingly manufacturers are measuring at a more realistic operating temperature of 85°C to satisfy the demands of the end users. Many parameter shifts occur with temperature; therefore, measuring closer to the final operating temperature improves the accuracy of the extrapolation of device characteristics. For example, Cree has reported that typically the color shift from 25°C to 85°C is around $\Delta u'v' = 0.002$, or approximately 2 standard deviations of color matching (SDCM) [16]. Lumen output is also typically reduced by 5% to 10% at the higher temperature, and the forward voltage generally drops by around 0.1 V. A project to develop an advanced high-speed, hot test tool is currently underway within the Program. The project uses laser heating of the phosphor to reduce testing times and aims to provide the industry with a pathway to 1 or 2 SDCM of color accuracy. (See Appendix B for more detail.)

Improvements in process controls plus the application of in-line testing and inspection will tighten device performance distributions, and allow manufacturers to develop product that more closely aligns with customer demand. Significant developments have been made in this sector, as evidenced by the release of an increasingly wide range of products with significantly tighter color bins. Array products introduced under Cree's Easywhite™ label are guaranteed to fall within either a 2 or 4 SDCM bin while covering a wider range of color temperatures. Philips Lumileds introduced their own range of products offering "*Freedom from Binning*" at the start of 2011. These products are guaranteed to fall within a 3 SDCM bin when measured at 85°C. More recently, Philips Lumileds introduced the LUXEON Z ES micro-sized warm-white illumination-grade LEDs, which were the first to offer 1 SDCM binning [17].

While there has been a noticeable improvement in process control, further improvements are required throughout the epitaxial growth, wafer-processing, chip production, and chip-packaging stages. There remains a strong need to develop improved in-situ monitoring and active process control for MOCVD epitaxial growth, in conjunction with rapid in-line characterization of the epitaxial wafers for rapid feedback to the manufacturing process. There is also a need for in-line testing, inspection, characterization, and metrology equipment throughout the LED package manufacturing process. Yield losses at each step in the manufacturing process have a cumulative effect; therefore, the ability to detect manufacturing problems at an early stage (excursion flagging) enables problems to be corrected, or noncompliant products to be excluded from further processing. Both actions can have a significant impact on overall production yield and can provide significant cost savings.

As tolerances continue to be tightened, there is a need for improved characterization equipment offering higher levels of sensitivity and accuracy to enable rapid and effective incoming materials qualification throughout the supply chain, and assure the quality and consistency of LED products.

Test and inspection equipment for luminaire and module manufacturing will involve equipment to validate incoming components, to perform in-line testing, to obtain photometric characteristics for completed products, to perform burn-in testing, and complete long-term reliability testing to identify potential failure mechanisms. Typically the industry employs computer-controlled goniophotometers in conjunction with integrating spheres to test luminaires. An example of equipment used for high-speed photometric testing of luminaires is shown in Figure 2.5. Such equipment is used to measure luminaire output, efficacy, intensity distribution, and zonal lumen density, and is able to automatically run an entire indoor photometric test in as little as three minutes. The testing method for SSL luminaires is well established and described in detail in IES LM-79 *Approved Method: Electrical and Photometric Measurements of Solid State Lighting Products* [18].

Figure 2.5 High-Speed Moving Mirror Goniophotometer Model 6400 T
Source: Lighting Sciences, Inc.

Manufacturers of test and inspection equipment for LED die and package manufacturing include the following:

- KLA-Tencor, Accent Optoelectronics, Cascade Microtech, and Orb Optronix in North America
- Laytec, Bede, Bruker, Cameca, Instrument Systems, and SUSS MicroTec in Europe

Manufacturers of test and inspection equipment for luminaire manufacturing include the following:

- Lighting Sciences Inc., Gamma Scientific, Radiant Zemax, Labsphere, and SphereOptics in North America

Many test laboratories have also been established to provide independent luminaire performance and compliance testing including (in the U.S.):

- Gamma Scientific, Intertek, Lighting Sciences, and SGS

2.2 LED Manufacturing Materials

2.2.1 Substrate Materials

A handful of substrate options exist for the manufacture of high-power GaN-based LEDs covering a range of materials (sapphire, silicon carbide (SiC), silicon (Si), and GaN) and diameters (e.g., 2”, 75 mm, 100 mm, and 150 mm). Currently, sapphire and SiC substrates dominate the market, although inroads are being made by both Si and GaN substrates. The substrate Roadmap continues to support two paths: (i) improved substrates for heteroepitaxial growth (sapphire, SiC, and Si), and (ii) improved substrates for homoepitaxial growth (GaN). In the case of SiC and sapphire substrates, improvements in substrate quality (e.g., surface finish, defect density, and flatness) and product consistency, in conjunction with the introduction of larger diameters, is required in order to meet the demands of high-volume manufacturing. For GaN substrates, the major issue impacting adoption is the very high substrate cost, inconsistent quality, limited supply, and the unavailability of larger diameters.

Both sapphire and SiC substrates have been used to produce GaN-based LEDs with state-of-the-art performance, and sapphire has established itself as the dominant substrate type used in production. A general trend toward larger substrate diameters is anticipated, mimicking the Si and GaAs microelectronics industry. Philips Lumileds has been manufacturing LEDs on 150 mm sapphire wafers since the end of 2010 [19] and Osram Opto started moving its standard production of GaN-based LEDs to 150 mm diameter sapphire substrates early in 2012 [20]. The move to 150 mm sapphire substrates has been accompanied by the release of SEMI standard SEMI HB1-0113 (see Appendix A), which will help ensure a steady supply of high-quality substrates at reasonable prices. Similarly, Cree has established a 150 mm SiC manufacturing line at its facility in North Carolina. Substrates are internally sourced.

Patterned Sapphire Substrates (PSS) have been a mainstay of the Asian market for a number of years and are widely used in the manufacture of mid- and low-power LEDs for backlighting applications. PSS involves nano-scale patterning of the substrate surface, which can improve light extraction and reduce epilayer defect densities. PSS can simplify the manufacturing process and reduce costs but has in the past generally resulted in lower performance than that achieved using conventional sapphire substrates. However, recent advances in manufacturing technology, including the project work being supported at Philips Lumileds[e], have suggested that performance does not necessarily have to be compromised using PSS.

A number of other manufacturers such as Azzuro, Osram Opto, LatticePower, Plessey, TSMC and Toshiba are developing capabilities based on 150 to 200 mm Si substrates. An example of GaN-based LEDs processed on a 200 mm Si substrate is shown in Figure 2.6. One proposed advantage associated with the use of 200 mm Si substrates is access to existing empty or underutilized 200 mm Si microelectronics wafer fabrication facilities. The absorbing nature of the silicon substrate means that it must be removed during the manufacturing process, which necessitates a thin-film technology approach, creating some processing complexity. LatticePower was an early adopter of this technology and commenced volume production of GaN-on-Si die in June 2012 [21]. In June 2013, Toshiba launched its first products (LETERAS™) based on this technology and Plessey introduced its MAGIC LED product. Both companies offer primarily medium- and low-power products based on PLCC SMT packages, although Toshiba does market a 1 W product using the 6450 package.[f]

[e] Results from the earlier project were reported at the 2013 Manufacturing R&D Workshop [47]. The current project is described in Appendix B.
[f] To see the full specifications of the product, visit http://www.toshiba-components.com/LEDS/.

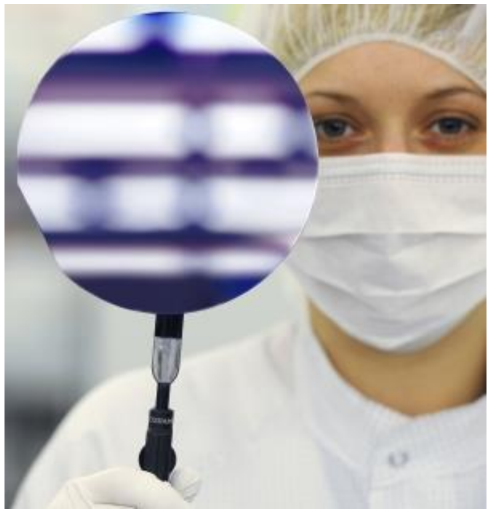


Figure 2.6 GaN-based LEDs on a 200 mm Silicon Wafer
Source: OSRAM Opto Semiconductors

As mentioned earlier, the major LED wafer manufacturers have either established, or are in the process of establishing, production lines based on 150 mm diameter sapphire or SiC substrates. Due to the small size of the LED die, and the escalating cost of up-scaling production equipment, the drive to move to larger substrate diameters is relatively limited and a general move to 200 mm for the established sapphire and SiC manufacturers is probably some years off.

The situation for GaN substrates is rather different. Such substrates offer the prospect of simplified device structures and epitaxial growth processes, and improved device performance. Soraa, Inc. has pioneered the use of GaN substrates for SSL and offers a range of MR16, PAR, and AR replacement lamps based on their “GaN-on-GaN” technology [22]. However, the availability of larger diameter substrates is limited and expensive, and existing production is performed using small substrates. In order for GaN substrates to become more than a niche application and reach the mainstream, they will need to be available with high quality and at a reasonable price in at least 100 mm diameter but preferably 150 mm diameter. Scaling bulk GaN to such diameters presents a formidable challenge; however, alternative approaches described above using a template approach offer some promise (see Figure 2.7).

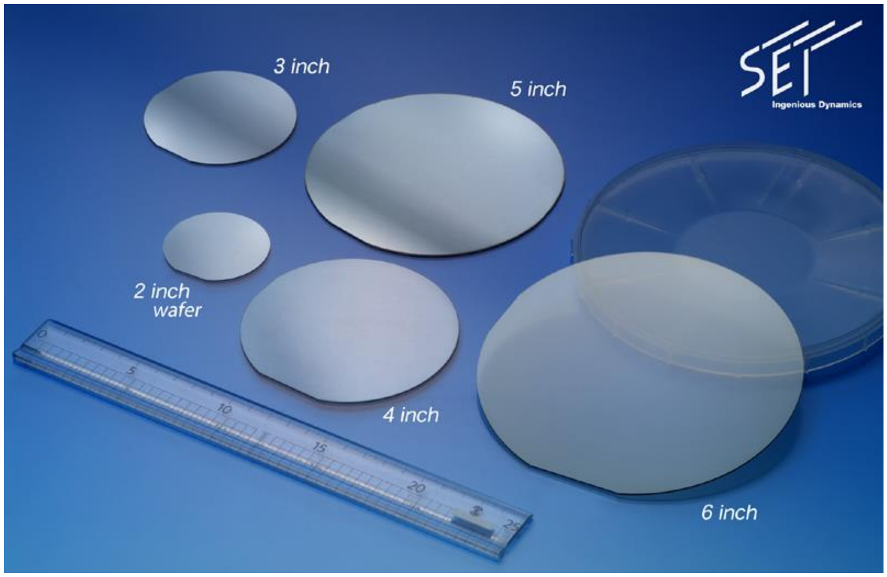


Figure 2.7 Bulk GaN Substrates
Source: Sumitomo Electric Industries

By far the most commonly used substrate is sapphire, for which the main substrate manufacturers include the following:

- Rubicon and Silian in North America
- Monocrystal in Europe
- Astek, STC, LG Siltron, and Samsung in Korea
- Crystalwise Technology (CWT), USIO, TeraXtal, and ProCrystal in Taiwan
- Crystaland in China
- Kyocera and Namiki in Japan

GT Advanced Technologies in North America is a major supplier of sapphire substrate manufacturing equipment and of sapphire boules to the substrate manufacturers. According to Yole Développement, the sapphire substrate supply market at the end of 2012 reflected the growing capacity in China due to government stimulus measures [23]. According to IHS Inc., the growth in the sapphire market during 2013 has been particularly strong, with demand rising 70% over 2012 [24]. This growth has been driven by the developing SSL market and the introduction by Apple Inc. and other smartphone makers of sapphire as covers for camera lenses and home buttons. Previously, the sapphire manufacturing capacity was primarily located in North America and South Korea, and these regions continue to provide the highest quality material and larger substrate diameters. PSS substrates, often patterned by the LED manufacturer, are now being patterned in-house by some sapphire manufacturers or via various foundries.

Cree is essentially the only manufacturer using silicon carbide substrates and manufacture their substrates in-house in North America.

Suppliers of GaN substrates and templates include the following:

- Kyma in North America

- Ammono, St. Gobain, and Soitec in Europe
- Mitsubishi Chemical Corp, Hitachi Cable, and Air Water Inc. in Japan

More recently, the projected use of silicon substrates has increased as companies seek to establish manufacturing operations and has introduced a range of silicon substrate suppliers to the LED market.

2.2.2 Chemical Reagents

The most important chemical reagents in terms of their impact on device performance and manufacturing cost are those used in the epitaxial growth of the semiconductor structure. These include the metal organic sources TMG, TMI, and TMA, and the gaseous sources ammonia (NH_3), hydrogen (H_2), and nitrogen (N_2). The purity of these reagents is critical to the LED performance and only the very highest purity and most expensive sources can be used. In addition, it is common to include point-of-use purification to achieve the highest levels of purity for optimum quality and consistency. From a cost perspective, the most critical reagents are TMG and NH_3, due to the fact that the majority of the structure comprises GaN material and a very high V/III ratio is required for optimum material quality, requiring large flow rates for the NH_3 gas.

The main metal organic reagent suppliers include the following:

- SAFC Hitech and Dow Electronic Materials in North America
- AkzoNobel in Europe

The main hydride gas suppliers include:

- Air Products in North America
- Linde Industrial Gases and Air Liquide in Europe
- Showa Denko KK and Matheson Tri Gas in Japan

Point-of-use gas purifiers are provided by companies including the following:

- SAES Pure Gas and Pall Corporation in North America
- Linde Industrial Gases in Europe
- Matheson Tri Gas in Japan

2.2.3 Packaging Materials

The LED package provides mechanical support and protection for the die, creates external contact pads for electrical and thermal connection to the die, and optimizes light extraction. The packaging of high-power LED die is currently based around the use of a ceramic substrate. Despite its higher price, the ceramic is generally AlN due to its improved thermal properties compared to alumina, the previous substrate of choice. Copper is used to produce the contact patterns on the front and rear of the substrate, and copper filled via holes provide interconnection between the front and rear patterns. A typical completed LED package is shown in Figure 2.8(a). Such packages are compatible with SMT.

Despite calls by the luminaire manufacturers for standardized package sizes and footprint, the LED package manufacturers have seen the need to produce an ever wider array of package designs to satisfy the demands of the SSL market. Most recently, the high-power, high-efficacy LED package that originally enabled the LED lighting market has been joined by less costly low- and mid-power LED packages originally developed for the backlighting industry. These smaller and lower power devices use inexpensive plastic packaging materials and come in a range of standard sizes. Their use in lighting-class products has become possible due to increases in lumen output and rapid improvements in efficacy. Due to their low cost, such devices can be used in large numbers to cover a wide area and are well suited to the creation of diffuse light sources. Figure 2.8 shows a comparison between a typical high-power and mid-power LED package.

Figure 2.8 Comparison of Typical High- and Mid-Power LED Packages
Source: Philips Lumileds

PLCC packages for low- and mid-power LEDs follow the standard nomenclature for SMT packages such as 5630, 3535, and 4014. The package name reflects the physical footprint with, for example, a 5630 package having a 5.6 x 3.0 mm footprint. Typically, two or four leads are provided (PLCC-2 or PLCC-4, respectively) and are wrapped around to the base of the package for surface mounting. In many, but not all, cases a standard 1.27 mm pitch is employed for the leads. An alternative to the PLCC package which is finding its way into high-power LED packaging, is the Quad Flat No-lead (QFN) plastic package, which shares a lot in common with the PLCC package but instead of leads has pads located on the base of the package. However, while most manufacturers have chosen plastic packages for their mid-power LEDs, Cree has recently introduced ceramic-based versions (XH-G and XH-B), which they argue are more stable with regard to practical operating temperatures and currents.

An alternative approach being investigated to reduce costs is to mount the LED die directly on an FR4, ceramic or MCPCB. Such technology is referred to as chip-on-board (COB). The MCPCB is most commonly used in this application and incorporates a base of metal material (normally aluminum), which acts as the heat spreader, a dielectric polymer layer with high thermal conductivity as a thermal interface layer, and an upper metal circuit layer (normally copper). The extension of this approach to a flexible PCB is also possible and is referred to as chip-on-flex (COF). Longer term, it may prove possible to mount the die directly on the heat sink.

There are many manufacturers of ceramic substrates and MCPCB materials, although according to LEDinside, Taiwan dominated the global production of ceramic thermal substrates in 2011, accounting for more than 70% of total shipments [25]. Manufacturers include the following:

- Bergquist Company, Cambridge America, CofanUSA, DuPont, and Laird Technologies in North America
- Chin-Poon, Gia Tzoong, HolyStone, Iteq, Leatec, Polytronics Technology, TA-I Technology, Taiflex, Tong Hsing, Univacco Technology, and Viking Technology in Taiwan
- Zhuhai Totking in China
- Denka, Kyocera, and NRK in Japan

Typically, the completed packages are mounted on tape and reel for use in pick-and-place SMT equipment.

2.2.4 Down-Converter Materials

Phosphors and other down-converter materials, plus their associated matrix materials, comprise a significant portion of the packaged LED cost. Part of the cost is associated with the raw materials themselves, especially for the more specialized red phosphors and quantum dot (QD) materials that are being developed for warm-white LED packages. A second part of the cost is associated with the need to provide uniform and reproducible application of phosphors to achieve a high level of control over the final color coordinates, and hence the ultimate device yield, which directly affects cost. Phosphor application, including the use of remote phosphor elements, is described in more detail in Section 2.4.2.

Improvements are required in the manufacturing of the phosphor or down-conversion materials in order to lower costs and produce more uniform and reproducible materials characteristics. Areas for materials improvement include the realization of more uniform particle sizes, better controlled morphology, better chemical stability, better thermal stability, and more consistent excitation characteristics. In terms of manufacturing improvements, the introduction of continuous processing methods (as opposed to batch-processing methods) has the potential to significantly reduce phosphor manufacturing costs. In addition, the development of materials compatible with manufacturing at lower temperatures and pressures would help simplify the manufacturing process. Much of the manufacturing technology for garnet, aluminate, and silicate-based phosphors (yellow/green emission) is well established; however, an improved low-cost batch manufacturing process for nitride-based red phosphors is required to efficiently handle the higher temperatures and pressures involved [26].

Batch-to-batch variations in phosphor powder (e.g., particle size, color point) lead to a significant amount of wastage of expensive materials since new batches must be qualified prior to use in the manufacturing line. This qualification generally involves a trial-and-error mixing approach to establish the transfer functions, which diverts effort and uses up material. Part of the reason for a trial-and-error approach is the current limitation in accurately characterizing phosphor powders and their interaction with matrix materials. Powder-level measurements include the determination of excitation, absorption, and emission characteristics, decay lifetime, quantum efficiency, particle size distribution, and reliability with respect to high temperatures and humidity, and incident flux. Many of these tests lack standardized measurement methodologies and accurate calibration standards, and the acceleration factors for reliability testing are not well established [27]. Similarly, complex interactions between the phosphor powder and the silicone matrix material create the necessity to test for compatibility in application and assembly [28].

Figure 2.9 Examples of LED Phosphors
Source: Intematix Corp.

Major suppliers of phosphors and down-converter materials to the industry include the following:

- Intematix, Dow Electronic Materials (formerly Lightscape Materials), Philips Lumileds (internal), GE (internal), Phosphortech, QD Vision, and Nanosys in North America
- Merck and Osram Opto (internal) in Europe
- Nichia (internal), Mitsubishi Chemical Corp, Shin-Etsu, and Denka in Japan

2.2.5 Encapsulation and Matrix Materials

Silicone is generally used as the primary encapsulation material and as the matrix for down-converter materials. Silicone may also be used for the molded lens. The silicone that is used must be stable with respect to exposure to high-intensity blue emission and to heat.

The silicone matrix materials are being pushed to their limits by the high photon fluxes and high thermal loads being generated by high-performance LEDs. The materials are subject to issues including volatile organic compound-induced transient browning, thermally induced permanent browning, and silicone cracking. Only certain grades are able to avoid degradation as a function of this exposure and show good long-term stability. Unfortunately, premium-grade silicone materials are very expensive and a significant cost factor in LED manufacturing. Lower cost alternatives with the requisite optical stability are required.

Companies manufacturing "LED-grade" silicone include the following:

- Dow Corning, NuSil, and Momentive Performance Materials (InvisiSil) in North America
- Wacker Chemie (LUMISIL) in Europe
- Shin-Etsu in Japan

2.3 LED Die Manufacturing

The principal manufacturers of LED die for SSL applications include Cree, Philips Lumileds, Bridgelux, Soraa, SemiLEDs, and Luminus Devices in North America; Osram Opto in Europe; Nichia, Toyoda Gosei, Toshiba, and Sharp in Japan; Epistar, FOREPI, Everlight, and Kingbright in Taiwan; Samsung and Seoul Semiconductor in South Korea; and Elec-Tech Opto, Epilight, HC SemiTek, and Sanan Optoelectronics in China. The LED die manufacturing process comprises epitaxial growth of the active device layers on the substrate, processing of the semiconductor wafer to define individual devices, and dicing of the wafer to produce individual die.

2.3.1 Epitaxial Growth

Epitaxial growth remains the key enabling technology for the manufacture of high-brightness (HB)-LEDs. The basic building block for a GaN-based LED is the n-GaN/InGaN/p-GaN heterojunction, although the actual structure will be significantly more complex. Each layer in the structure must be deposited with a high degree of control over thickness and composition of each layer, and the interfaces between layers must be carefully delineated. Subtle changes in layer structure and growth methodology can lead to very significant changes in device performance, and remain a closely guarded secret by the manufacturers.

GaN-based HB-LED epiwafers are currently manufactured using MOCVD. Significant progress has been made over the past few years with support through the SSL Manufacturing Initiative. The latest generation of MOCVD reactors described in Section 2.1.1 offer improvements in uniformity, reproducibility, controllability, and throughput.

Areas for future development include the need for an improved knowledge of growth mechanisms and related chemistry, as well as the implementation of active process control using in-situ monitoring. Computational fluid dynamics (CFD)-based modeling is used extensively in the development of improved equipment and processes. However, more work is required in this area.

The focus on uniformity and reproducibility improvements must continue, along with the focus on reducing costs. Table 2.1 describes a set of suitable metrics to characterize the epitaxy process. The most critical metrics are those associated with epiwafer uniformity and reproducibility. The table sets targets for in-wafer uniformity, wafer-to-wafer reproducibility, and run-to-run reproducibility. The epitaxial layer cost will depend to a large extent on the total layer thickness (e.g., growth time, precursor usage) and wafer yield. There is no common substrate type or diameter, epitaxial growth reactor configuration, or total layer thickness. Consequently, it was decided to normalize the epitaxial layer cost to layer thickness (μm) and wafer area (cm^2), as shown in Table 2.1. The epitaxy metrics have been updated based on inputs received at the 2014 Manufacturing R&D Workshop. The cost metrics anticipate ongoing improvements in wafer throughput (shorter cycle times and increased numbers of wafers/run) and in epiwafer yield (improved wavelength uniformity and wafer-to-wafer/run-to-run reproducibility).

Table 2.1 Epitaxy Metrics

Metric	Unit	2014	2015	2017	2020
Wafer uniformity (standard deviation of wavelength for each wafer)	nm	1.5	1.25	1.0	0.75
Wafer-to-wafer reproducibility (maximum spread of mean wavelength for all wafers in a run)	nm	1.5	1.25	1.0	0.75
Run-to-run reproducibility (maximum variation from run-to-run of the mean wavelength for all wafers in a run)	nm	1.0	0.9	0.80	0.75
Cost of ownership (COO)	-	50% reduction every 5 years			
Epitaxy cost	$\$/\mu m{\cdot}cm^2$	0.25	0.20	0.15	0.10

Source: 2014 Manufacturing Workshop attendee consensus

2.3.2 Wafer Processing

The next stage for the epitaxially grown LED wafer is the fabrication of individual die. The epitaxial wafer is delivered to the wafer processing line, which may be co-located in the same facility or, as is more often the case, may be located in a different geographical location. Many of these process lines for the major manufacturers are located in Asia. For example, Philips Lumileds has located its 150 mm wafer-processing facility in Singapore.

Wafer processing involves patterning of the semiconductor layers to separate the individual die and expose different surfaces. Metal layers are then deposited to form the n- and p-contacts. In certain designs the n- and p-contacts are formed on the upper surface; in other designs they might be formed on separate upper and lower surfaces, or might involve the use of holes in order to form both contacts on the rear. Dielectric layers are used to passivate the structures and provide electrical isolation.

To a large degree, the lithographic, etching, deposition, and metallization processes employed in the fabrication of GaN-based LEDs are similar to those used successfully for other semiconductor materials. Major differences revolve around the etchant chemicals, etchant gases, and contact metals employed for the AlGaInN materials system, and the need in many cases to completely remove the substrate to facilitate contacting (e.g., removing the insulating sapphire substrate) and efficient light extraction (removing the refractive index step between epitaxial layer and sapphire, which inhibits light passage, or removing the absorbing Si substrate). Substrate removal is generally achieved by mechanical grinding to remove most of the material, followed by a final separation, which may be achieved by laser lift-off (for sapphire), by chemo-mechanical polishing (for sapphire or SiC), or by purely chemical means (for silicon substrates). The resulting thinned wafer is normally bonded to a carrier to provide mechanical support during subsequent process steps.

Hence, the wafer processing stage in the manufacturing process is largely well established. Nevertheless, process revisions and innovations continue to reduce costs and improve performance. One example is the trend toward larger diameter wafers to reduce manufacturing costs. Philips Lumileds realized significant cost reductions when implementing their recent transition from 75 mm (3”) to 150 mm diameter wafers, as shown in Figure 2.10.

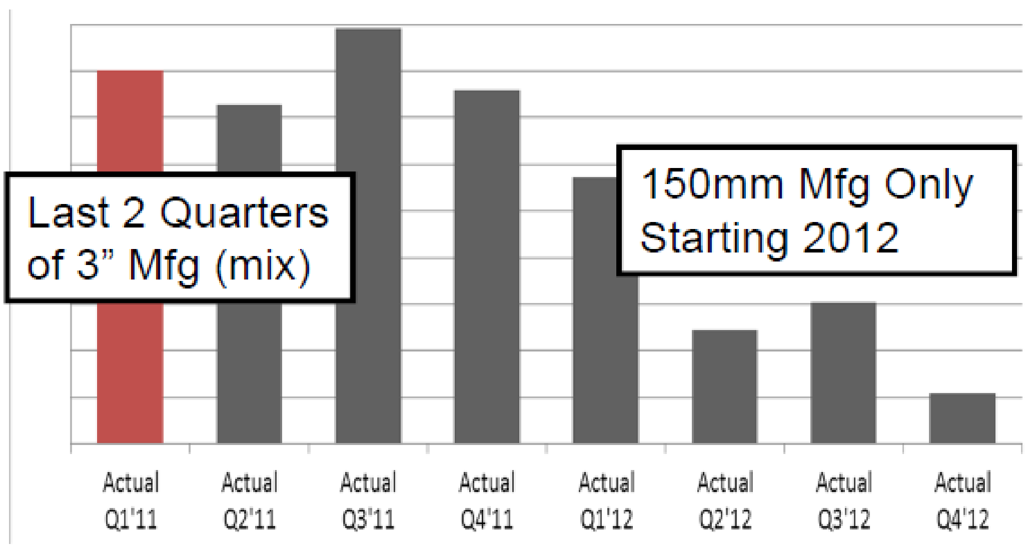


Figure 2.10 Reduction in Relative Manufacturing Cost when Transitioning from 3” to 150 mm Diameter Wafers

Source: Iain Black, Philips Lumileds, SSL Manufacturing Workshop, Boston, MA, June 2013

Another example is the introduction of multiple die architectures and types, which has necessitated a move toward a more modular or building block approach to mitigate the growing complexity. A significant area for future innovation appears to be in the development of new lateral structures and the monolithic integration of components on the same semiconductor wafer.

One example of how wafer processing developments can enable new device functionality or performance is in the area of high-voltage die. Lithographic patterning and controlled semiconductor etching can be used to segment a single die into many smaller die connected in series. A single die has a forward operating voltage around 3.0 V; therefore, by segmenting it into a large number of smaller die connected in series, it is possible to produce a composite device with a much higher operating voltage, which can simplify the driver design and enable it to operate at higher efficiency.

Taking this approach a step further, we can consider combining semiconductor layers for different types of devices on the same wafer and using more sophisticated processing technology to monolithically integrate different functions on the same chip. For example, this approach might allow us to monolithically integrate optoelectronic, electronic, and microelectromechanical functions.

Integrating increasing amounts of functionality at the wafer level is an excellent approach to cost reduction providing that the performance is not compromised. The more that can be achieved before the wafer is diced up, the less that will need to be accomplished at an individual die level where the cost per die will be much higher. One example of process simplification might be the deposition of a phosphor layer prior to wafer dicing and separation. Another example might be the use of wafer-level packaging techniques developed in other semiconductor technology areas such as in the production of complementary metal-oxide semiconductor (CMOS) cameras for cell phones. Such methods might allow a significant proportion of the packaging to be completed at the wafer level, and could offer the prospect of highly automated optical and electrical testing prior to final assembly.

Yet another example is the introduction of PSS substrates, which can simplify the wafer processing by mitigating the need to remove the substrate and roughen the wafer surface, saving on processing costs. This geometry can also simplify the packaging requirements, saving on packaging costs, and, due to its robustness, could even remove the need for a package by lending itself to direct chip-on-board SMT assembly. The potential for cost reduction over a thin-film flip chip approach is illustrated in Figure 2.11. In other LED chip architectures, SiC chip shaping is employed to improve light extraction from the chip, which provides very high efficiencies in a low-cost chip fabrication process.

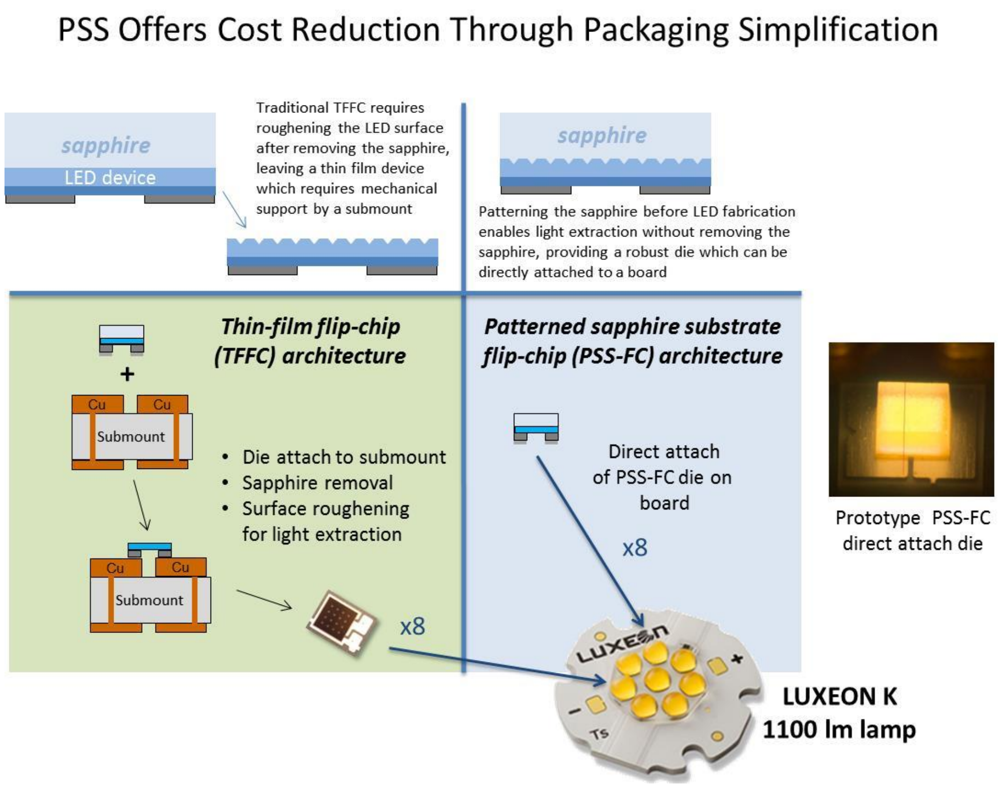


Figure 2.11 Comparison of Current TFFC Manufacturing Approach with PSS Approach
Source: Joseph Flemish, Philips Lumileds

2.3.3 Die Singulation

The processed wafer comprises a large number of LEDs in a regular repeating pattern. The LEDs must next be separated into individual die. To do so the wafer must be cut in some way, either by sawing, cleaving, or laser ablation. Prior to cutting the wafer, it is normally thinned in order to facilitate the singulation process. As described in the previous section, the substrate may be removed completely from the active layers during wafer processing. If this is not the case, then the substrate must be thinned by grinding and chemo-mechanical polishing.

Prior to cutting, the wafer is normally mounted on a flexible adhesive film. The flexible film is subsequently expanded to separate the die, and allow individual die to be pick-and-placed onto a tile, sub-mount, or package.

LED die will generally be probe-tested at this stage and binned. Testing will be performed under pulsed conditions at 25°C in order to determine the peak or dominant emission wavelength and the radiometric output power.

2.4 LED Package Manufacturing

The LED package remains a key component within the LED-based luminaire and represents a significant cost element. Efforts to reduce costs while continuing to improve performance will require concerted action throughout the manufacturing supply chain. Such efforts will focus on higher quality and lower cost raw materials, improved epitaxial growth equipment and processes, optimized wafer processing equipment, and more efficient packaging methods and equipment. Various raw materials feed into the manufacturing process such as substrates, phosphors, gases, and chemicals (described in Section 2.2).

The same companies listed in Section 2.3 that manufacture LED die also manufacture LED packages, although it should be noted that these operations are mostly carried out in Asia. In general, they will make use of their own die but on occasion they will use die from other manufacturers. Beyond these tier 1 manufacturers there are a number of companies that rely entirely on other manufacturers for their die. These include Lextar, Lite-On, Unity Opto, Nationstar, Shenzhen Jufei, Honlitronic, and Refond in Asia.

An outline of the LED package manufacturing process is provided in the following sections.

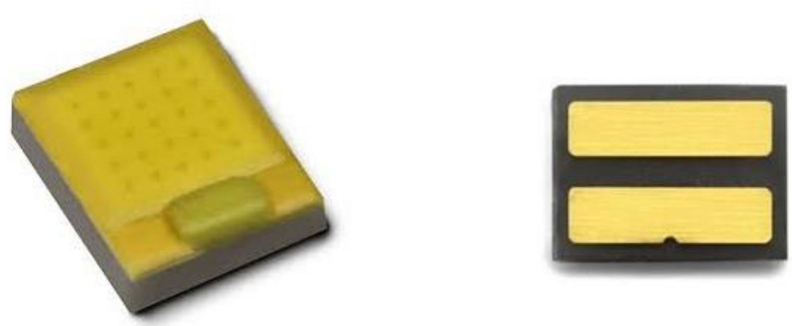
2.4.1 Die Packaging

Die packaging is heavily based on equipment and processes developed for the general semiconductor die packaging industry. Certain customization has been required but to a large extent existing equipment is already suitable. There is a high degree of commonality with regard to packaging materials such as ceramic packages and sub-mounts, and surface mount technology. Similarly, the industry has been able to employ many of the existing processes and equipment for die-attach, wire bonding, flip-chip, encapsulation, and lens attach. Probably the most critical difference occurs in the controlled application of a phosphor or other down-conversion material to the die to create a phosphor-converted white LED.

There are a multitude of options regarding the packaging of LED die in terms of the package design and packaging materials employed. A manufacturer can have as many as 50 different package families and within each family there are multiple variants based on lumen output, Vf, CCT, CRI, and binning tolerance. Ultimately, the package design reflects the target application, and the end result is a wide range of different types of package in terms of physical dimensions and light output characteristics. For example, package dimensions can vary from 1.3 mm x 1.7 mm (Lumileds LUXEON Z) to 35 mm x 35 mm (Cree CXA3590) with viewing angles from 90 to 145 degrees. Package families might be designed to offer higher lumen output, higher efficacy, lower cost, improved color quality, tighter color control, or some optimal combination of these attributes. Offering a broad product mix ensures that an optimal design exists for each lighting application, whether it is for an omnidirectional source or a high center beam intensity directional source.

Traditionally, the focus has been on the manufacture of high-power 1 W packages comprising a single 1 mm^2 die and producing around 80-100 lumens of white light. Such packages use relatively expensive ceramic materials on account of their superior thermal properties. A more recent trend has been to utilize lower power LED packages originally developed for the backlighting industry. Such products use inexpensive plastic packaging materials, resulting in very low-cost packages. While the lumen output per package is much lower, it is possible to use many more packages to achieve similar overall light output levels in a cost- effective manner. Low-cost plastic packages are well suited to the manufacturing of diffuse lighting sources, while compact, high-power packages are well suited to the manufacturing of high-intensity point sources. In this context, it has been common to refer to medium-power and high-power packages to distinguish between plastic packages with power dissipations of around 0.5 W or less, and ceramic packages with power dissipations over 0.5 W. However, the recent introduction of 1 W products based on plastic quad flat no-lead (QFN) packages by companies such as Nichia (757 series) and Toshiba (TL1F1 series) is blurring these lines.

In common with the die manufacturing process, there has been a growing trend in LED package manufacturing toward modularization to cope with the ever-widening portfolio of package designs. One approach being employed by Philips Lumileds is to identify a small number of basic building blocks, which can be combined in many different ways to produce a range of different product configurations, from compact single die packages to larger COB arrays and modules. The LUXEON Z ES package is an ultra-compact (1.6 mm x 2.0 mm), high-performance surface mount package and epitomizes the design of a simple compact building block. The package is shown in more detail in Figure 2.12 and is only slightly larger than the die area (1.4 mm x 1.4 mm). Each LUXEON Z ES consists of a high-brightness InGaN LED die on a ceramic substrate, covered by a yellow-colored phosphor layer. The ceramic substrate provides mechanical support and a thermal path from the LED chip to the bottom of the package. An interconnect layer electrically connects the LED chip to cathode and anode pads of equal size on the bottom of the ceramic substrate.



(a) (b)

Figure 2.12 LUXEON Z ES White LED Package: (a) top view and (b) rear view
Source: Philips Lumileds

The modularization concept is illustrated in Figure 2.13. The LUXEON T employs the same high-power, thin-film flip chip (TFFC) die on ceramic sub-mount with conformal phosphor coating as the LUXEON Z ES. The difference is in the application of a dome on the LUXEON T to achieve higher extraction efficiency. Thus, LUXEON Z ES has the highest brightness and smallest source size, while LUXEON T has the highest efficacy. The LUXEON MZ and M at the top of the figure are analogous to the LUXEON Z ES and T, respectively, but with four times more die area. The LUXEON S is a close-packed array of LUXEON Z ES packages mounted on a board to achieve high brightness and small source size; the LUXEON K is an array with slightly larger spacing to accommodate domes for higher efficacy. The LUXEON K is therefore essentially an array of LUXEON T packages, although the encapsulation is done at the board level, not at the emitter level.

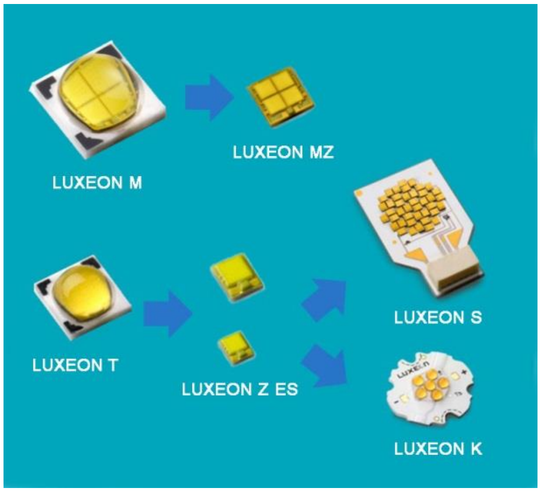


Figure 2.13 Examples of Modularization in LED Package Manufacturing
Source: Iain Black, Philips Lumileds, SSL Manufacturing Workshop, Boston, MA, June 2013

Die packaging remains a major cost component for the packaged LED and the main challenge is therefore to reduce packaging costs. This might be achieved by getting more light out per package or more efficient use of raw materials (either using less material or finding more affordable alternatives) to enable the manufacturing of lower cost LED packages without compromising on performance. Using advanced silicone and thermal packaging materials enables higher current and higher temperature operation, enabling more light output, effectively reducing the cost or package (per lumen). The recent move to lower power operation and plastic packages for lighting class LEDs provides a major cost saving. Such packages use smaller, and therefore cheaper, die and since they operate at low powers, they don't require expensive thermal solutions such as the use of ceramic materials and metal-clad printed circuit boards (MCPCBs). However, they do not provide the lumen maintenance behavior seen from high power packages.

Multi-die packages are commonplace with many identical die configured in regular arrays. Such packages provide large lumen outputs. Future developments in packaging technology are likely to involve the integration of different types of die to create new functionality. One example is the integration of an AlGaInP-based red/amber LED die with a white LED die to achieve higher efficacy and improved color quality [2]. Another example might involve the integration of multiple monochromatic LEDs to achieve a white light source with high efficacy, high CRI, and tunability over a wide range of color temperatures. Electronic components might also be integrated with the LED die such as the driver integrated circuit (IC), or sensors and control ICs.

2.4.2 Down-Converter Application

The application of phosphors or other down-converter materials to achieve high-quality white light of the specified color quality and color point requires careful control of material composition and layer thickness. As the color coordinate tolerance is tightened, it is often necessary to employ a tunable phosphor application process where each die is tested prior to phosphor application to achieve the target color point. The availability of more uniform and reproducible phosphor materials would help eliminate such matching processes and reduce costs.

In a high-mix manufacturing line offering a full-range product platform, there might be 6 to 8 CCTs and 2 to 4 CRIs, creating 24 or more phosphor solutions per LED platform. The manufacturer has many options available to him to control these parameters, including the choice of blue LED pump wavelength, phosphor conversion strength (phosphor loading and thickness), phosphor color points, and choice of phosphor materials [29]. In addition, the high-mix product environment leads to material inefficiency due to the need for a finite stabilization period when switching between mixtures. An application system is required that can quickly dial-in and stabilize a new mixture and given color point in order to reduce costs. There are many different methods available to apply the phosphor to the blue die such as the relatively simple “dam & fill” method, the use of a molded phosphor loaded film, the use of a conformal coating such as by electrophoretic deposition or depositing a silicone/phosphor mix, the use of phosphor-loaded ceramic disc (e.g., Lumiramic), or the use of a remote phosphor dome. Different package types suit different application methods, with the “dam & fill” method largely confined to medium-power LEDs using plastic packages and to chip-on-board packages, while the conformal methods used for high-power LEDs use ceramic packages or volume emitting die. Remote phosphors are generally applied as a coating to optical elements positioned above and around the semiconductor die (e.g. the Vio® product manufactured by GE Lighting uses a remote phosphor dome in conjunction with a violet LED).

The choice of application method affects many characteristics of the final package and will be carefully chosen for each package family. A conformal coating is often preferred over a molded film to achieve improved color point consistency, as shown in Figure 2.14. The LUXEON Z ES shown in Figure 2.12 and the related LUXEON T package shown in Figure 2.13 are good examples of the use of a conformal phosphor coating applied to a high-performance TFFC die to achieve state-of-the-art efficacy and tight color control. Further improvements in application flexibility to meet the wide range of demands for current and new package designs are required, along with suitable equipment to meet that demand.

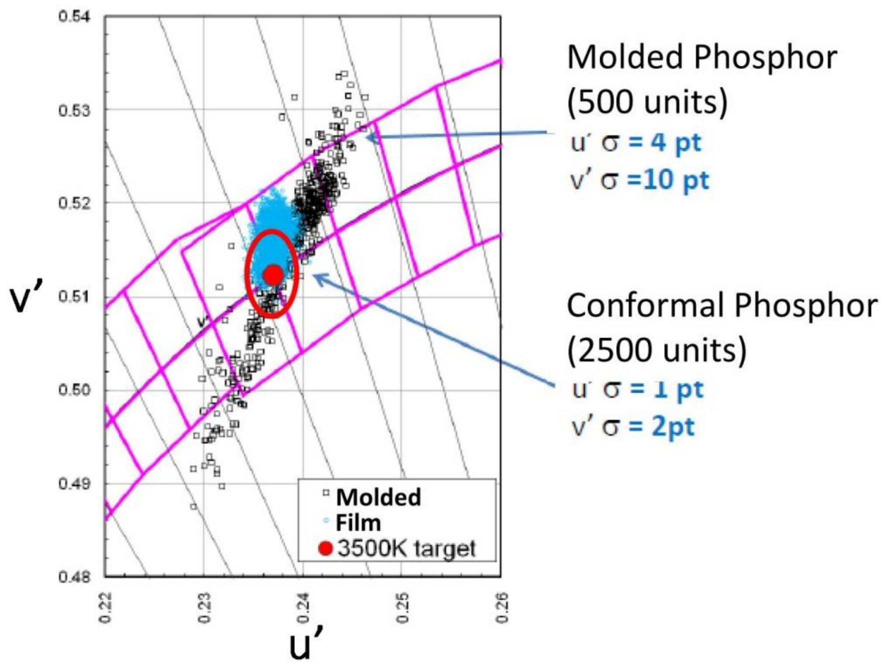


Figure 2.14 Comparison of Color Point Control for Molded and Conformal Phosphor Films
Source: Jim Neff, Philips Lumileds, SSL Manufacturing R&D Workshop, 2014

2.4.3 Encapsulation and Lensing

The LED die is encapsulated to provide environmental protection. Encapsulation is generally accomplished through the application of a silicone-based dielectric layer. Only certain grades of silicone material are suitable for this application, since they must be stable with respect to the elevated operating temperatures and high optical flux densities. Often the encapsulation is in the form of a molded lens over the LED, or less commonly a separate lens can be attached above the encapsulation layer. The lens assists with the efficient extraction of light from the LED and controls the emission characteristics.

As described in the previous section, it is common for the silicone material to provide a matrix for the phosphor or down-converter material. In this case, the phosphor/down-converter material is dispersed within the silicone matrix prior to being deposited over the LED die.

2.5 LED Luminaire Manufacturing

Manufacturing of an LED luminaire involves combining the LEDs with mechanical and thermal components such as the heat sink, optical components to tailor the light distribution, and LED driver electronics. The various subsystems are discussed separately below before considering the complete luminaire.

2.5.1 LED Die and Packages in Luminaires

LED die or packages are a critical component of all LED-based luminaires, and luminaire manufacturing revolves around integrating the LED source with the other luminaire components to achieve the required form factor, and the optimum balance between cost performance, product consistency, and reliability. Since the beginning of the DOE SSL Manufacturing R&D effort, Workshop participants have consistently supported R&D in the areas of current droop and IQE as a means of reducing the relative cost contribution of LED packages within the luminaire. Improved LED efficiency and reduced droop will not necessarily reduce the cost of LED components (and may make them more expensive) but would reduce the number of expensive LED components required in a luminaire design and reduce the amount of thermal handling for a given lumen output. In addition, consistent, efficient, and stable emitters are desired across the visible spectrum. These LED R&D topic areas are appropriate for the Core Technology Research or Product Development activities and are discussed in the 2014 MYPP. While advances in LED component performance continue to be made, luminaire manufacturers continue to adjust their product designs and manufacturing processes to use the most appropriate LED packages that are available.

From a manufacturing R&D perspective, there are alternative LED die or package-related strategies that can be employed to reduce luminaire cost. A key metric to be optimized is the lumen output per dollar (lm/$) and improvements can be achieved in two distinct ways. One approach mentioned above is to drive a high-power LED package at higher currents in order to achieve higher lumen output. Fewer LED packages will be required but the lumen output gains will be at the expense of efficacy. Nevertheless, continuous improvements in package efficacy have made this approach practical. An alternative approach gaining traction in the industry is to utilize lower cost plastic packages originally designed for the display backlighting industry. Such packages are much cheaper; therefore, they can be used in large numbers to achieve a specific lumen output while retaining a high lm/$, and recent improvements in efficacy and color quality control have made this a viable option for high-performance luminaires in certain applications. This latter approach is particularly attractive for distributed lighting sources such as tube replacements or omnidirectional lamps or luminaires.

Significant progress has also been made in terms of reducing performance variability for LED packages. Binning of LED packages in terms of lumen output, CCT, and forward voltage, is still routinely performed by the manufacturer; however, increasingly, this testing is performed at temperatures closer to the luminaire operating temperature (85°C) and most product is guaranteed to fall within 4 to 5 SDCM, with certain products available in 1 to 2 SDCM bins at a premium price. Manufacturers are therefore able to select product that closely meets their performance requirements, although costs will increase as the specification is narrowed. In order to achieve tighter tolerances while maintaining competitive prices, some manufacturers have developed sophisticated mixing approaches to make use of lower cost products falling further from the black-body locus. Regarding color consistency, there is a need for ongoing research into the sensitivity of the market to color variations – what is humanly visible and what is the tolerance for variations in color and output with respect to the lighting application? A common scheme involves mixing a white LED with a red or amber LED but more complex schemes using larger mixtures of colors can be considered. In such situations, color and output shift with time and temperature for different color LEDs must also be dealt with in the product design and manufacturing processes. Such luminaires may require the integration of optical sensors and control systems, although simpler control systems have been successfully developed using control algorithms for the white plus red mixing scheme.

2.5.2 Remote Phosphors

Phosphor or down-converter material is normally applied at the package level; however, it can also be applied at the luminaire level. Phosphor conversion at the luminaire level is achieved by the use of a phosphor-coated optical material placed some distance above blue-emitting LEDs. This method is referred to as a remote phosphor. The main advantage of using a remote phosphor is that the flux density of light hitting the phosphor is reduced so temperature rise in the phosphor is reduced, although thermal management of the phosphor material must still be considered. Reducing the temperature rise in the phosphor reduces thermal quenching within the phosphor, which maintains the phosphor efficiency and enables a more consistent color point. Another advantage is that the blue emission from the pump LEDs can be averaged to provide a more consistent color point. The main disadvantages are that much larger volumes of phosphor material must be used, deposition uniformity must be maintained over larger areas, and the optical system between the LED and remote phosphor may be more complex.

A good example of a lamp using the remote phosphor approach is the Philips A19 L•Prize bulb shown in Figure 2.15.

Figure 2.15 Philips A19 L•Prize Bulb
Source: http://www.usa.philips.com

Companies such as Intematix in North America are able to supply sheets, or custom-molded shapes, of remote phosphor material (ChromaLit™) with well-defined performance characteristics when combined with blue LEDs.

2.5.3 Optical Component Manufacturing

Luminaires incorporate a variety of optical elements to optimize light extraction and tailor the light distribution. These elements might be refractive, reflective or diffusive in nature, depending on the application. Recently, there has also been a discussion of integrating the secondary optic into the thermal management of the luminaire. This is only feasible if a more thermally conductive optical material, such as glass, is used. The benefits of this approach could be reduced thermal demands on the heat sink and providing some heat to the front face of the luminaire, which could melt ice buildup and keep the optical path clear from snow or ice.

Manufacturers of optical components include CARCLO, LEDiL, Khatod, WhiteOptics, and Luminit.

2.5.4 LED Driver Manufacturing

Drivers remain a critical component in all LED-based luminaires and can significantly impact luminaire performance and reliability. They are most often cited as the cause of failure for luminaires. Features built into the driver such as controls can add value to LED lighting products.

Most of the issues associated with drivers remain the same, as discussed in previous revisions of this report. These issues are more related to product performance and cost trade-offs than they are to manufacturing technology. The manufacturing of drivers is well understood and can be done at low cost if the product performance requirements are well understood.

While basic driver manufacturing technology may be well understood, the need for drivers with improved integration, reliability, flexibility, and form factors within the luminaire remains. Approaches for the development of flexible, high-efficiency, low-cost drivers could include the disaggregation of driver functionality into sub-modules to allow luminaire integrators to mix and match functions while maintaining high efficiency and reliability. The manufacturing of drivers with some level of controllability and control compatibility is also a concern for driver and luminaire manufacturers. Luminaires for varying lighting applications may require different types of control. Internal electronic control of color consistency, compatibility with multiple dimming systems, or communication with various forms of wired or wireless controls may be required for the lighting application and this functionality is typically integrated into the power supply. The need for the integration of these controls into the luminaire can impact the assembly costs of the luminaire, as well as the reliability of the luminaire. Improvements to the design and manufacturing of drivers and the control systems could have a significant benefit on luminaire cost, performance, and reliability.

Previous calls have been made for a standard report format of driver performance to facilitate driver integration into LED-based luminaires. The lack of information and inconsistent reporting of driver performance inhibits efficient and easy integration of the electronic components. It was also felt that a standard reporting format would facilitate the use and development of analysis, simulation, and design tools for luminaire manufacturers. The sidebar lists a number of parameters that should be included in such a report. Nevertheless, despite these calls, there has not been any significant movement on this issue.

Proposed driver information:

- Operating temperature range
- Efficiency with respect to power, load, and temperature
- Input voltage and output voltage variation
- Off-state power
- Power to light time
- Power overshoot
- Transient and overvoltage protection specifications
- Compatibility with specific dimming protocols
- Compatibility with ambient light sensors
- Harmonic distortion in power supply
- Output current variation with temperature, voltage, etc.
- Maximum output power
- Power factor correction

There is also a need to develop a testing protocol to better define driver performance and reliability. In this case some progress has been made. For example, an American National Standards Institute (ANSI) lighting group committee is currently working on an LED driver testing method (ANSI C82.XX) and a driver performance standard (ANSI C82-SSL1-20XX). Also, the DOE SSL Program is supporting product development R&D to better understand and predict driver reliability.

Manufacturers of complete driver sub-assemblies include the vertically integrated luminaire manufacturers and specialist driver manufacturers such as iWatt in North America, and Meanwell in Taiwan. Luminaire manufacturers have recently been acquiring these specialist driver manufacturers. For example, GE Lighting acquired Lightech in July 2011 and Acuity Brands acquired eldoLED in March 2013. LED driver IC manufacturers include (listed alphabetically) Allegro Microsystems, AnalogicTech, Analog Devices, Austriamicrosystems (AMS), Cirrus Logic, Diodes, Inc., Exar, Fairchild Semiconductor, Freescale Semiconductor, Infineon Technologies, Intersil, iWatt, Leadis Technology, Linear Technology Corp., Macroblock, Marvell, Maxim Integrated Products, Monolithic Power Systems, National Semiconductor (now part of Texas Instruments), NXP Semiconductors, ON Semiconductor, O2 Micro, Power Analog Microelectronics, Power Integrations, Richtek, Rohm Electronics, Semtech, Silicon Touch Technology, Skyworks, STMicroelectronics, Supertex, Texas Instruments, and Toshiba.

According to MarketsandMarkets, Inc., the Asia-Pacific region dominates the LED driver IC market, capturing a 59.6% share of the close to $1 billion market [30]. This is mainly due to the low manufacturing cost, presence of original equipment manufacturers/original device manufacturers (OEMs/ODMs), and favorable government tax exemptions. In 2010, display backlighting accounted for around 80% of the market but will decrease to around 66% by 2015 due to the more rapid growth being experienced by the lighting segment (46.5% CAGR).

2.5.5 Lamp and Luminaire Manufacturing

LED-based lamps and luminaires have a similar level of integration but lamps use a standard electrical interface for use within conventional lighting fixtures. Manufacturing of LED-based lighting products shares little in common with conventional lighting products since conventional lighting technologies tend to be based around the fixture-plus-bulb paradigm, with the manufacturing of each part handled completely separately, often by separate companies. The integrated nature of an LED-based lighting product, where fixture, light engine, and driver electronics are typically combined in a single unit, significantly complicates the manufacturing process. Luminaire manufacturers have successfully addressed the challenge by introducing manufacturing technologies more commonly seen in the consumer electronics industry, simplifying the materials and manufacturing processes, introducing system-level design optimization methodologies (including DFM and DFA), and by developing improved testing capabilities. Some important themes currently being discussed include the following:

- Reducing Interfaces
  One method to simplify the manufacturing process is to streamline the integration of the luminaire by simplifying interfaces between the subcomponents of the luminaire. Within

the LED luminaire product there are opportunities to better integrate the LED die, LED package, or LED module with the lamp mechanical, electrical, and optical structures. Such advancements could simplify the design of the lamp or luminaire products, simplify the manufacturing of these products, and reduce product costs. The potential for high levels of component integration within LED-based luminaire products will have a significant impact on how such products will be manufactured. This level of integration may require automated manufacturing to bring down the assembly costs and reduce human variations in the manufacturing process. This integration also represents a challenge for existing luminaire manufacturers who may not have the necessary tools or expertise to develop the LED-based products. For example, the LED chip could be mounted directly to the luminaire heat sink, removing several layers of material and thermal interfaces, if an appropriate manufacturing method could be developed. This would remove the distinction between the LED package or light module and the luminaire. This is just one example, but the thermal, mechanical, optical, and electrical interfaces could all be considered for enhanced integration.

- Novel Materials
  Novel materials could also be considered that might simplify manufacturing and reduce the complexity, cost, and weight of the luminaire. Luminaire manufacturing would benefit from lighter weight and lower cost heat sinks and thermal handling materials. Luminaire and LED modules could benefit from lower cost but similarly robust optical materials. New materials could even serve multiple purposes, such as optical materials that can dissipate heat as part of the thermal handling system or heat sinks that also serve as the "circuit board." There are numerous areas of the luminaire where advanced, novel materials could improve performance and reduce cost.

- Novel Form Factors
  Most LED-based lighting products replicate the form factors of conventional lamps or luminaire products. This enables easy replacement into existing fixtures and provides a sense of comfort for consumers who may be skeptical of new form factors. However, forcing LED lighting technology into legacy form factors reduces performance and increases cost of the lighting products. For example, with the common A19 lamp form factor, the screw-in Edison socket does not provide a thermal path to dissipate heat from the LEDs, and the required optical distribution is difficult for LEDs to match. New luminaire form factors could maximize LED lighting performance while reducing cost and delivering appropriate light levels. However, such products will require rethinking of existing lighting systems and possible redesign of how lighting is integrated into buildings.

- Modularization
  A modular approach to luminaire manufacture, by developing standardized form factors and interfaces between subcomponents, would allow for a consistent integration process regardless of the supplier of the subcomponent. This approach is being considered and

supported by the Zhaga Consortium[g]. The components of the luminaire, such as the LED light engine, driver, thermal handling, and optics, and housing, could be developed to readily fit together in a variety of configurations. This could enable rapid manufacturing of a broad range of products, reduce inventory demands, and simplify luminaire design. All of these benefits could lead to greatly reduced luminaire costs. The modular approach could also benefit smaller scale and traditional luminaire manufacturers who could more easily and rapidly design and manufacture LED-based lighting products. While the modular approach offers many advantages, there are inevitable performance compromises since the general-purpose modules cannot be optimized for each specific lighting application. Often, the modular approach will contain more individual piece parts that can increase cost over a holistic design. The modular approach to the design and manufacturing of LED-based lighting products will likely exist in parallel with products that take the opposite approach of reducing interfaces and highly integrating sub-components.

- Efficient Testing
  A further approach to simplifying the manufacturing process is to simplify luminaire testing requirements. It has been suggested that this could be partially achieved by changes to testing policies and standards. In terms of manufacturing R&D, testing simplification could be accomplished through a more consistent supply of incoming components, particularly LED packages. Testing the luminaires at critical points in the manufacturing process and relating the test results to final luminaire performance could also simplify testing (see Section 2.6.4). Lastly, design modeling software could enable more rapid product design with a range of incoming components and anticipate product performance (see Section 2.6.2). In-line testing and design software could also expedite the development of similar products within a product family, enabling a more flexible manufacturing process. For example, common subcomponents used in the manufacture of a range of final products could be tested before the manufacturing process diverges.

A large and growing number of companies are involved in the manufacturing of LED-based luminaires and modules. Historical lamp manufacturing companies such as Philips, Osram Sylvania, GE, and Toshiba; luminaire manufacturers such as Cooper Lighting (now Eaton), Acuity Brands, Hubbell Lighting, and Zumtobel; and many new entrants to the lighting industry including Cree, Lighting Science Group, LG, Soraa, and Samsung have all begun manufacturing LED-based lighting products.

A critical aspect of luminaire manufacturing that was highlighted at both the Roundtable meeting and the Workshop was color consistency – at both initial deployment of the luminaire and over its lifetime. Luminaire manufacturers must still contend with incoming LEDs with noticeable color variations even within the same bin. And now, as many more products are being sold, customers and manufacturers are seeing unacceptable color shifts over time, not just due to shifts in the LED but also from changes in the optical system of the luminaire such as discoloration of the secondary optic or of the reflective surfaces. Different lighting applications require different tolerances for color stability and different luminaire architectures have demonstrated different

[g] More information on the Zhaga Consortium can be found at: http://www.zhagastandard.org/about-us/vision/.

levels of susceptibility to color shift. The message from luminaire manufacturers was that it would be highly beneficial to understand and, eventually, be able to model the color shift of products over time based on the design of the product and the application environment. With this information, luminaire manufacturers could better design luminaires with the appropriate color shift tolerance for a specific lighting application.

2.5.6 Test and Inspection

Test and inspection requirements associated with luminaire manufacturing include sub-assembly testing, in-line inspection, and end-of-line electrical and photometric testing. Incoming sub-assemblies must be tested and inspected in order to ensure they meet specification. Often this is performed by the sub-assembly manufacturer. In-line visual inspection is employed in order to detect manufacturing problems at an early stage and allow affected parts to be reworked or scrapped. However, the most significant test and inspection activity is associated with end-of-line testing of the completed luminaire.

The introduction of LED-based lighting technology has significantly complicated the lamp and luminaire manufacturing process compared to conventional lighting products. In particular, testing requirements have become much more significant due to the fact that each LED-based luminaire is a unique fixture comprising a number of subcomponents. Each LED-based lighting fixture has its own distinct electrical and photometric performance characteristics and must be separately tested (absolute photometry). Conventional lighting technologies tend to be based around the fixture-plus-bulb paradigm, which allows for simple and rapid photometric testing with readily anticipated results (relative photometry).

The impact of test and inspection on yield, cost or performance of the final product will depend on the point in the manufacturing process that the measurement is made. These critical testing points need to be identified and exploited for their benefits to the manufacturing process. Luminaire testing currently culminates in a raft of specific compliance tests to demonstrate adherence with the requirements dictated by a number of agencies, including Underwriters Laboratories Inc. (UL), DesignLights Consortium (DLC), and ENERGY STAR (see Section 4.2). The industry is working with these compliance bodies to understand how this testing burden might be minimized.

2.6 LED Modeling and Simulation

Modeling and simulation is an important activity in the design and manufacturing of the various components and subsystems, and of the manufacturing process itself. Modeling of the impact of manufacturing actions on LED and luminaire performance can help improve the new product design process and provide an accurate prediction of final device performance and reliability. The most important types of modeling and simulation being applied to SSL manufacturing are discussed in the following sections.

2.6.1 Cost Modeling

Understanding the source of costs within the manufacturing process is critical to being able to minimize the cost of the final manufactured product. Cost modeling can be used to determine those costs and to help identify those areas which have the largest impact on final device and luminaire costs. A simple modular LED COst Model (LEDCOM) [10] was developed previously to describe the manufacturing of an LED package and was first demonstrated at the 2012 Manufacturing Workshop. The LEDCOM model is described in last year's Manufacturing Roadmap [31].

Modeling of the luminaire manufacturing process would follow the same approach, although the much larger range of possible form factors and product options precludes the development of a simple generic cost model.

2.6.2 Design for Manufacturing

In order to optimize manufacturing efficiency and reduce costs, it is necessary to take an integrated or holistic approach to system design, as shown in Figure 2.16. Design for manufacturing (DFM), assembly, cost, reliability, and maintainability serves as a starting point for integrated product development. Integrated product and process design occurs when system design engineers and manufacturing engineers work together to design and rationalize both the product and production and support processes. The objective is to optimize all the manufacturing functions including fabrication, assembly, test, procurement, shipping, delivery, service, and repair, and at the same time assure the best cost, quality, reliability, regulatory compliance, safety, time-to-market, and customer satisfaction. It has been shown that decisions made during the design phase determine 70% of the product's costs while decisions made during the production phase account for just 20% of the product's costs. Further, decisions made in the first 5% of product design could determine the vast majority of the product's cost, quality, and manufacturability characteristics.

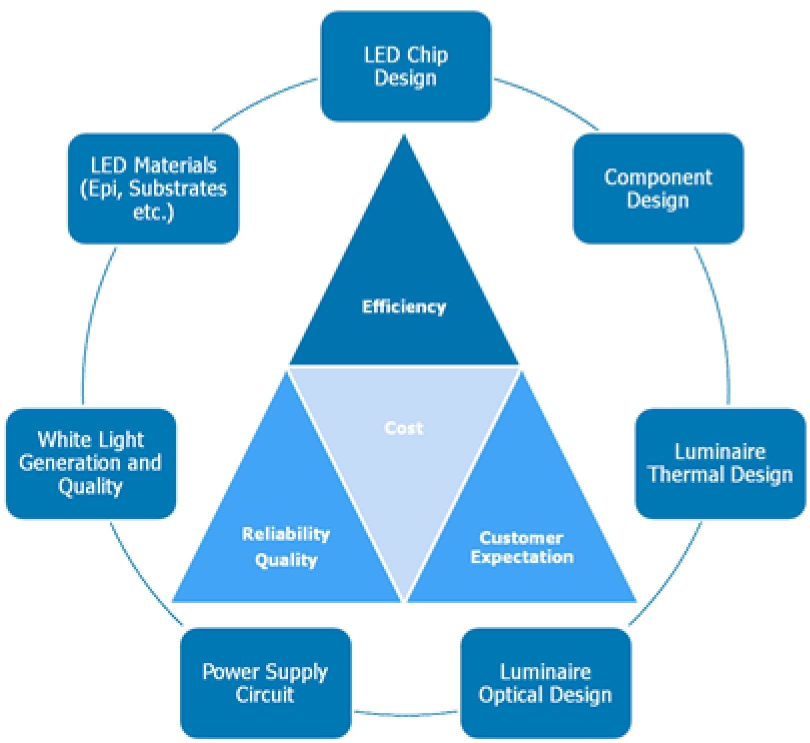


Figure 2.16 Integrated Systems Approach to SSL Manufacturing
Source: Mark McClear, Cree, Inc., SSL Manufacturing Workshop, Vancouver, OR, June 2009

DFM and integrated product design involve various approaches, including: using common parts and materials, minimizing the number of active or approved parts through standardization, designing for ease of assembly (DFA), and creating robust designs which avoid tight tolerances beyond the natural capability of the manufacturing processes.

2.6.3 Manufacturing Process Simulation

Modeling of the manufacturing system can be performed in order to understand the impact of manufacturing or assembly changes on the final product. Process modeling can be used to determine how well a manufacturing process will make the product and is able to predict the impact of changes at a product level on the process, and minimize the need for additional process testing. Process modeling is done at various levels ranging from modeling of the process flow in the manufacturing facility, to modeling of an individual process step, to modeling of the underlying physical processes.

A range of tools is available to perform these tasks, including discrete-event modeling and simulation (DES), and physics modeling. DES is used to predict cycle times and throughput, identify bottlenecks, and perform what-if analyses for reconfiguring factories. Physics modeling is used to obtain an improved understanding of the underlying physical processes using tools such as computational fluid dynamics or finite element analysis.

One key element to the success of such modeling and simulation is the need to populate the models with real-time information that is collected automatically and continually. The model is refined and optimized using this information to enable it to most accurately match the observed outcomes, and ultimately to most accurately predict the impact of changes to the manufacturing process on the observed outcome. The development of suitable test and measurement equipment (see Section 2.1.5) therefore goes hand-in-hand with the development of a manufacturing process model.

2.6.4 Luminaire Reliability Modeling

The lack of a thorough understanding of lifetime for LED-based luminaires continues to be a significant problem for luminaire manufacturers. While LM-79 provides a standardized protocol for measuring luminaire performance and can be performed at various points in the luminaire life, it is expensive and time consuming to perform this test, particularly at the rate new luminaire and lamps products are being developed. LM-79 also does not offer a means to accelerate life testing to allow for interpolations of lifetime within a shorter test cycle. The LM-80 test protocol can be used to measure the lumen depreciation of the LED packages or modules that are used in a luminaire or lamp system. This information can be used as the upper limit for lumen depreciation since integrating the LED packages or modules into a luminaire will introduce additional lumen depreciation mechanisms, particularly in the optical system. However, lumen depreciation does not define the reliability of the luminaire. Other failure mechanisms such as catastrophic failure and unacceptable color shift must also be considered in order to understand the reliability of the system.

This year many attendees of the Roundtable Meeting and Manufacturing Workshop were interested in discussing color shift in luminaires. At the Workshop, a panel discussion was devoted to the topic. Color shifts may be associated with the LED package (LED, phosphor, or encapsulant), the optics (lenses or reflectors), or even the power supply. Changes in any of these components can lead to a noticeable and unacceptable color shift in the luminaire [32]. Color shift has always occurred with conventional light source technologies, but some early negative experiences during the introduction of LED technology have raised customer awareness and sensitivity to color variations, and generally heightened expectations [33]. In general, color shift over the long lifetime of the LED-based luminaire needs to be better understood to the point where long-term color performance can be modeled and consumers can be ensured of long-term color stability.

Uncertainty in the long-term performance of the luminaire system makes it difficult to estimate and warrant the lifetime of LED-based luminaires. It also hinders manufacturers’ ability to know how best to improve their product reliability. This uncertainty could be addressed by better information about long-term performance of key LED luminaire components and materials, including the LED packages, drivers, optical components, and materials used in assembly, along with accepted methods to statistically predict luminaire system lifetime.

2.7 LED Manufacturing Priority Tasks for 2014

DOE identified the following priority LED manufacturing R&D tasks based on discussions at the Manufacturing Roundtables and Workshop.

<table>
<tr><td colspan="3">M.L1. Luminaire Manufacturing: Support for the development of flexible manufacturing of state-of-the-art LED modules, light engines, and luminaires. Suitable development activities would likely focus on one or more of the following areas:

Advanced LED package and die integration (e.g., COB, COF) into the luminaire
More efficient use of components and raw materials
Simplified thermal designs
Weight reduction
Optimized designs for efficient and low-cost manufacturing (such as ease of assembly)
Increased integration of mechanical, electrical, and optical functions
Reduced manufacturing costs through automation, improved manufacturing tools or product design software

The work should demonstrate increased manufacturing flexibility (processes or designs that can work for multiple products) and higher quality products with improved color consistency, lower system costs, and improved time-to-market through successful implementation of integrated systems design, supply chain management, and quality control. The overarching goal of this work should be to accelerate consumer adoption, resulting in accelerated total energy savings.</td></tr>
<tr><td>Metric(s)</td><td>Current Status</td><td>2017 Target(s)</td></tr>
<tr><td>Lamp bill of materials (BOM) cost</td><td></td><td>33% reduction[h]</td></tr>
<tr><td>Assembly cost ($)</td><td></td><td>33% reduction[h]</td></tr>
<tr><td>Color control (SDCM)</td><td>Depends on application</td><td>Depends on application</td></tr>
</table>

- Participants noted that luminaire manufacturing faces complex, multifaceted issues in terms of materials selection, operating conditions, and environmental conditions.
- Participants agreed with the bulleted focus areas in the task description, although there was not consensus as to the most critical R&D focus areas.
- Some participants requested additional focus areas to cover the development of simplified, low-cost power supplies.

[h] Manufacturing cost reductions should be ahead of or in line with reductions projected in Figure 1.8, but may be adjusted for different product types.

M.L3. Test and Inspection Equipment: Support for the development of high-throughput, high-resolution, non-destructive test equipment with standardized test procedures and appropriate metrics. Such equipment might enhance test and inspection capabilities at various stages within the manufacturing line, such as for semiconductor wafers, epitaxial layers, LED die, packaged LEDs, modules, luminaires, and optical components. Equipment might be used for incoming product quality assurance, in-situ process monitoring, in-line process control, or final product testing/binning. Suitable activities will develop and demonstrate effective integration of test and inspection equipment in high-throughput manufacturing tools or in high-throughput process lines, and will identify and quantify cost of ownership improvements.		
Metric(s)	**Current Status**	**2017 Target(s)**
Throughput (single bin units per hour)		2x increase[i]
Cost of ownership		
$/units per hour		

- Participants noted that test and inspection in the earlier manufacturing phases can reduce failure risk and testing costs for the final luminaire.

M.L7. Phosphor Manufacturing and Application: Support for the development of efficient manufacturing and improved application of phosphors (including alternative down converters) used in solid-state lighting. Emphasis is to be placed on improving the quality and consistency of phosphors and down converter materials, and optimizing the quality, consistency, and long term stability of such materials when applied in the final product. It is anticipated that the influence of the matrix materials will need to be considered in conjunction with the development of novel application approaches to achieve improved color quality and consistency of the packaged LED or lamp/luminaire.		
Metric(s)	**Current Status**	**2017 Target(s)**
Material usage efficiency		
Δ u'v' control	0.006[j]	< 0.003[k]
Materials cost ($/kg)		10% reduction per year
(D90-D10)/D50 (conventional phosphor)	30	10

[i] Work should enable or accelerate cost reductions in accordance with those shown in Figure 1.6 and Figure 1.8.
[j] Center to edge. Applies to full distribution of LEDs (not at luminaire level).
[k] For white LED at fixed blue wavelength.

3 OLED PANEL AND LUMINAIRE ROADMAP

At present, lighting panel products that are suitable for general illumination are manufactured using vapor deposition techniques on small-scale lines. These panels are built on rigid, display-grade glass using batch processes and multi-emitter stacks or tandem structures and have efficacies up to 60 lm/W. Encapsulation is accomplished with a glass cover and light output is enhanced using external extraction films. This approach is too costly, however, and the efficacy is limited without the use of internal extraction mechanisms. Many avenues are being explored to lower cost and improve performance, and some impressive prototype panels have been demonstrated. For instance, Panasonic has demonstrated 100 cm^2 panels that deliver 133 lm/W at 1,000 cd/m^2 using high-index substrate materials and internal light extraction schemes.[1] Konica Minolta has reported 139 lm/W at 1,000 cd/m^2 with 15 cm^2 panels using all-phosphorescent materials, light extraction layers, and strategic organic layer structuring.[1] However, the manufacturability and cost of these higher performance products have not yet been demonstrated.

The imperative of manufacturing cost reduction means that approaches that maximize efficacy may not lead to the optimal commercial products. Most recent improvements in the performance of OLED panels have involved the use of double- or triple-stacked devices to reduce the current density and maximize lifetime as well as efficacy. This increases the cost (in $\$/m^2$) of manufacturing through the need for additional materials and reduction in the yield. Other researchers, for example, at Arizona State University (ASU) and the Semiconductor Energy Laboratory (SEL), are focusing on single-unit devices that will enable lower cost fabrication. SEL has demonstrated a single-stack hybrid panel of area 81 cm^2 with efficacy of over 140 lm/W. By balancing efficacy against lifetime and color quality, they showed a second panel with CRI of 87, improved lumen maintenance, and efficacy of 84 lm/W at 1,000 cd/m^2.

This chapter summarizes the manufacturing of OLEDs and highlights R&D areas in need of advancement. OLED materials (organic stack, substrate, electrodes, extraction layers, and encapsulation) that are currently used as well as those being explored are outlined, and the implications of materials choices on the manufacturing process are described. One of the key choices is whether to use solution or vapor deposition materials and processes. Higher efficacies and longer lifetimes are typically achieved using vapor deposition processing, but great progress is being made with solution-based materials and deposition techniques and cost savings can arise from implementation of such approaches, even if it is only for select layers in the device stack. The equipment required for vapor deposition and solution-based deposition is described and roll-to-roll processes are outlined. Finally, the processes involved in the manufacturing of OLED panels and luminaires are explained and a cost model for OLED manufacturing is presented.

3.1 OLED Design Considerations

The OLED community has not yet settled on an optimum manufacturing approach for cost-effective lighting panels. Choosing a successful approach involves optimizing performance while

[1] Demonstrations took place at SID Display Week 2014.

minimizing costs associated with materials, equipment, and processing. Increased collaboration among manufacturers is needed to narrow down the options and to enable high-volume manufacturing to be undertaken with confidence.

Some of the manufacturing strategy considerations are identified below:

- Dry (evaporation) versus wet (solution) processing
  Since the performance of wet-processed emitters is still lagging, short-term interest is in the use of coating processes for the anode structures, hole injection layer (HIL), and hole transport layer (HTL). This offers significant cost savings through the elimination of the lithography steps and subsequent higher utilization of the conducting materials. The techniques under evaluation include ink-jet and nozzle printing, screen printing, slot-die coating, and gravure printing. Although prototype panels have been produced by wet processing, no commercial production is underway.

- Substrate selection
  Glass is currently the most convenient substrate. Costly display-grade glass is the standard choice, but low-cost float glass substrates may offer a solution for cost reductions. The adoption of plastic has been delayed by the unavailability of cost-effective and reliable manufacturing techniques for defect-free barrier layers. Rapid atomic layer deposition is being explored as an alternative to standard deposition processes for the inorganic layers in multi-layer barriers, but its commercial viability has not yet been established. The use of metal foils as substrates has been confined to research laboratories. Many prototype plastic substrate panels have been demonstrated and several products are expected to be released in the coming year, for example, by LG Chem and Konica Minolta.

- R2R versus batch processing
  Currently, panels are produced using batch processes and this is the preferred approach for the near term while demand is low and materials/processes are still in development. It has been argued that R2R manufacturing simplifies substrate handling and so can increase total throughput. Experiments in Taiwan and Europe using both vapor deposition and solution processing have shown that this approach is feasible; however, there has been no demonstration that this approach offers substantial cost benefits in comparison with in-line batch systems. One of the problems is that R2R operation requires relatively large-scale production and thus large amounts of material, even at the R&D stage. It can thus be particularly expensive to produce panels while yields are low. However, as noted in Section 1.2.2, Konica Minolta is building a high-volume line that should provide valuable information on the viability of R2R manufacturing and plastic substrates.

- Complexity level
  Reduction in the number of organic layers could lead to lower capital costs and higher yields. Most plans to accomplish this involve solution-based processing, but it has not yet been shown that the DOE performance targets can be met using this approach.

- Throughput scaling

Most OLED proponents argue that substantial cost reductions can be achieved only through increased throughput from each line. Scaling in size will require substantial added capital investment. Cycle times well below 60 seconds are desired, but little progress has yet been reported. Others argue that uncertainties in the market size favor the development of less expensive equipment and better material utilization with modest throughput. The feasibility of this approach may become clearer in the next year through the experience of OLEDWorks [34].

3.2 OLED Manufacturing Materials

The laboratory performance of OLED materials is being steadily improved, as detailed in the 2014 MYPP. However, the cost of these materials is still a major concern, as is the integration of the various components in the manufacturing process. Materials constitute the majority of the manufacturing cost in flat-panel displays and most other forms of large-area electronics. It is anticipated that this will also pertain to OLED lighting once automation is introduced, more cost-effective tools are available, and the production lines are operating smoothly.

Here we discuss the manufacturing issues associated with the materials components of OLED devices: organic stack materials, substrates, light extraction layers, electrodes and current spreading layers, and encapsulation materials.

3.2.1 Organic Stack Materials

Organic stack materials include emissive layers (EML), hole and electron injection layers (HIL, EIL), transport layers (HTL, ETL) and blocking layers (HBL, EBL). Organic stack materials can be polymeric or small molecule materials. At present, most high-performance lighting panels employ small molecule organics deposited using vapor deposition techniques. Polymer materials have not yet demonstrated the high efficiency and lifetime that is achieved in small molecules, but are being explored because they work well with flexible substrates, can be aligned to aid in light extraction, and may potentially lead to lower deposition costs as they are more amenable to solution processing. Sumitomo Chemical has developed P-OLED inkjet-printing technology and their materials have been used by Panasonic to create a 56" printed OLED TV. They have also demonstrated these materials in flexible P-OLED lighting panels produced in an ink-jet printed process.

Though small molecules are typically formulated for evaporation, ligands can be attached to the molecules to create soluble small molecules. This approach is in development as it offers compatibility with solution processing as well as materials performance that is approaching that of evaporated small molecules. Companies such as Konica Minolta, DuPont, Pioneer, Universal Display Corporation (UDC), and Merck are working on soluble small molecule solutions.

Material costs represent a significant portion of the overall panel manufacturing cost (see Table 1.6). Cost reductions in stack materials can be realized when the following appertain:

- Materials utilization is improved.
- Materials sales volumes grow.
- More collaboration exists between suppliers to make affordable materials available.
- Materials stability and robustness improve.

- Compatibility between materials sets from different vendors has matured.

The primary route to reducing material costs is to minimize waste. For example, it has been estimated that less than 1% of the precious metals, such as iridium or platinum, that enter the supply chain are actually embedded in the final OLED product. Improvements in deposition equipment and yields should improve overall materials utilization. Material utilization rates of around 30% are common for vapor deposition equipment, while solution deposition techniques can be 90% or more. Another significant factor in the current pricing of materials is recovery of the cost of developing high-performance chemicals. While sales volumes are low, recovery of these costs can represent a major portion of the sales price for key materials. This factor should become less important as sales volumes grow, providing incentive to use similar materials to those used in OLED displays.

The most expensive organics are the phosphorescent dopants that are used in the emitter layer and the ion dopants in the transport layers. The phosphorescent dopants that are used today contain rare heavy metals, such as iridium. However, the layers are very thin (10-30 nm) and doping ratios are small, typically 5-10% by mass. Thus, the amount of dopant material in each emission layer is typically $3x10^{-3}$ g/m^2, of which around 25% is due to the heavy metal component. Many teams are working on iridium-free phosphorescent dopants and the DOE SSL program has supported such efforts at Pacific Northwest National Laboratory (PNNL) and the University of North Texas, and currently is funding a team led by Jian Li at Arizona State University looking into Pt-based emitters. Cynora is a German start-up that has been developing soluble copper-based emitter systems as a rare-earth-free alternative to iridium-based emitter systems. There are several manufacturers with the capability to supply phosphorescent dopants; however, the IP position held by UDC has proved so strong that all the commercial OLEDs use dopants that UDC supplies and that have been made by PPG.

There is a trend towards the use of relatively thick transport layers (up to about 500 nm) to reduce surface plasmon losses in the metal electrode and to guard against early electrical failures due to shorting. Nevertheless, the cost of the embedded ion dopants is much less than that of the glass substrates and other inorganic layers around the organic stack. Novaled (recently acquired by Samsung) has established a strong IP portfolio for ion dopants for small-molecule systems and is the sole supplier for commercial sales, with materials manufactured by BASF.

The availability of the remaining materials in the organic stack is less constrained by IP considerations. There is keen competition amongst Asian, European, and North American manufacturers, such as Hodogaya, Merck, Idemitsu Kosan, Nippon Steel Sumikin Chemical, and Solvay. However, the leading Korean panel manufacturers have been keen to encourage local production and capabilities have been developed by Samsung SDI, Daejoo, Dow Chemical, Duksan Hi-Metal, LG Chem, and Sun Fine Chemical. Potential suppliers from China include Aglaia, Jilin, Xi'an Ruilian, e-Ray Opto, Lumtech, and Nichem Fine Tech.

For materials that are deposited in vapor, stability against decomposition at high temperatures is critical in enabling deposition to be accomplished at high rates. Aixtron's solution to this issue is to use organic vapor phase deposition (OVPD) technology, which was initially developed at Princeton University. In this approach, the deposition rate is controlled by carrier-gas flow instead of evaporation temperature. Thus, the source material does not undergo heating cycles that lead to decomposition. Further, this approach decouples the source from the deposition chamber and is amenable to scaling. Aixtron has installed an R&D deposition cluster in their facility to demonstrate their processes to research partners and customers, and to further advance their own OLED R&D. Aixtron is working with Manz to develop a demonstration Gen-8 system.

In addition to temperature, sensitivity to water vapor and oxygen is important in determining the shelf life of the device. The use of more tolerant chemicals would simplify the tasks of deposition and encapsulation and several promising candidates have been explored. However, these have not yet been incorporated in commercial devices, so that encapsulation still represents a daunting challenge, as described below.

The compatibility of the various layers in vapor-deposited stacks is mainly of concern with respect to device design and performance. However, the chosen design can have implications in manufacturing, for example, if graded interfaces are needed. This issue can have more profound implications for solution processing, particularly with respect to solvent selection. If care is not taken, the solvent that is used in one layer can modify the structure of the underlying layers.

Since the drying of each layer is usually the slowest step in solution processing, compatibility with rapid drying techniques is critical. There are many other important considerations in the formulation of inks for specific printing techniques. The optimization of OLED materials and equipment for ink-jet and nozzle-jet printing has been studied for more than a decade, led by companies such as Seiko Epson, CDT-Sumitomo, and DuPont. More recently, similar studies have been conducted for contact printing methods, such as slot-die coating and gravure printing. Figure 3.1 summarizes the issues as seen by Plextronics (recently acquired by Solvay) for the deposition of their p-doped polymer materials used in thick hole injection and transport layers.

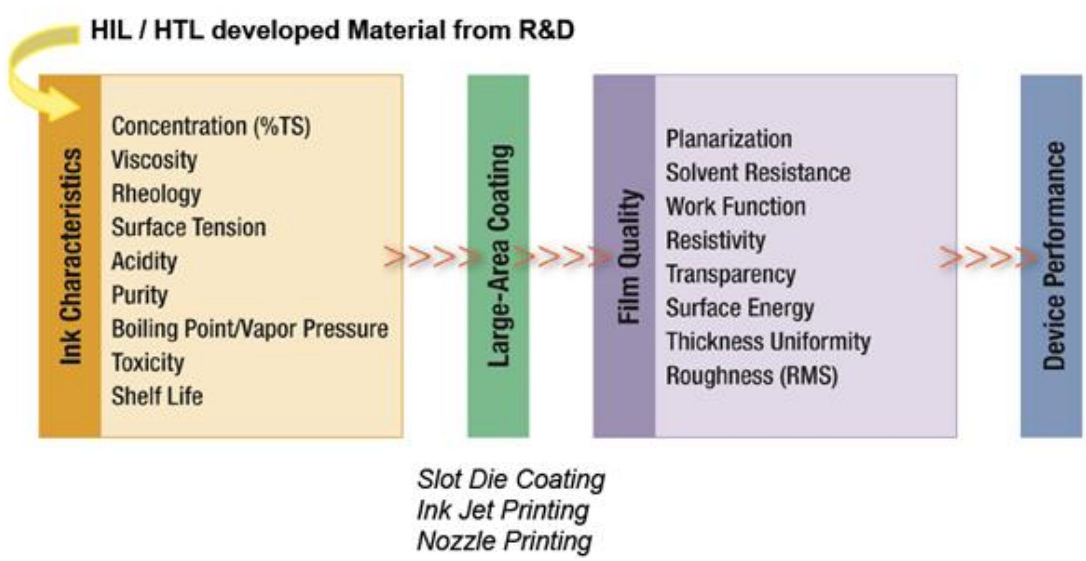


Figure 3.1 Important Ink Characteristics in the Deposition of HIL and HTL Materials
Source: John Mühlbauer, Plextronics, LOPE-C 2012, Munich

3.2.2 Substrates

While the OLED lighting industry has historically borrowed high-performance, display-grade glass substrates from the display industry, the cost of these substrates is very high, so alternatives are being explored, including the use of waste glass from display production.

One potential solution to lower substrate costs is low-cost glass. Through an SSL Product Development project, PPG Industries has demonstrated that soda-lime float glass can be used instead of the borosilicate glass used in OLED displays. This replacement for display-grade glass could lead to a five-fold reduction in costs, from around $35/m^2 to $7/m^2. This would bring the cost close to that of alternative substrates, such as metal foils or polymers (without a barrier coating). Float glass is impermeable, transparent, withstands high temperatures, and is stable and smooth. Further, common OLED structures and deposition techniques are easier to adapt to soda-lime glass as compared to other substrate options such as metal foils and polymers as its properties (transparency, chemical stability) are similar to those of borosilicate substrates, which have been the foundation for OLED development.

Despite its low cost, soda-lime float glass has yet to be adopted by panel manufacturers. The drawbacks of float glass are that it is heavy (up to 4 times the thickness of display glass, which is usually 0.5 – 0.7 mm thick), rigid, and fragile. Glass manufacturers such as PPG, Asahi Glass, Pilkington (Nippon Sheet Glass), and Guardian Industries are developing integrated substrate solutions with this material. It is possible that substrate products with integrated features (such as built-in light extraction and anode layers) will become available to panel manufacturers at a reasonable cost, and these substrates will be adopted for the next generation of lighting products.

As rigid, heavy float glass has its limitations, other substrate alternatives are being explored, including the following:

- Ultra-thin glass
- Metal foils
- Polymer substrates

Corning and other glass companies have developed ultra-thin (25–100 micron thick) borosilicate glass, such as Corning’s Willow Glass, that is conformable and can be envisioned for use in roll-to-roll mode. However, handling such thin, fragile glass is a challenge and small surface and edge defects can lead to cracking throughout the substrate. Furthermore, costs are high, but Corning has argued that the use of borosilicate glass simplifies the encapsulation process so much that the total cost can be compatible with DOE’s targets for integrated substrates. Fraunhofer COMEDD, an Institute in Dresden, also advocates the advantage of long lifetime using flexible glass substrates as compared with polymer-based substrates and encapsulation schemes. Using G-Leaf glass supplied by Nippon Electric Glass, Fraunhofer COMEDD has developed flexible lighting panels on their R&D R2R line.

Figure 3.2 NEG G-Leaf Ultra-ThinGlass
Source: NEG Website, http://www.neg.co.jp/glass/09.html

Work by Alcoa and others has shown that thin metal foils of steel or aluminum (Al) are another acceptable alternative for use in roll-to-roll processing with top-emission architectures. These substrates are thin, lightweight, durable, impermeable, and can assist in the thermal management of OLED devices. The cost of bare Al substrates can be as low as $1.5/m^2. Disadvantages are that they are only suitable for top-emitting architectures; they are prone to crease and wrinkle (particularly Al) and need to be polished and/or coated with a planarization layer to attain the smoothness required. In roll-to-roll production, metal foils offer better physical dimension stability and handle stress better than polymeric substrates.

Clear plastic substrates are being explored by companies such as Agfa, BASF, DuPont Teijin Films, and Samsung. A collaboration between UDC and ASU produced a flexible display on DuPont's Teonex substrate at the Flexible Display Center. Samsung is developing a polyimide substrate for flexible displays and LG Chem and Konica Minolta have demonstrated flexible lighting panels on plastic substrates. LG Chem was previously using a flexible glass substrate and a metal protective layer with LG Chem's Face-Seal encapsulation; however, they are now exploring polyimide substrates, which are more flexible and lighter weight, along with new substrate-coating technology and barrier solutions.

For OLED lighting, polymer substrates may reduce costs as they are compatible with R2R processing, which could improve materials usage and offer high throughput. Further, polymer substrates are lightweight, flexible, and durable, and structured surfaces can be formed on the substrates during production or by etching steps afterwards. Polymer substrate materials should be inexpensive, have a high glass transition temperature (to withstand the OLED fabrication process), and be highly transparent. Complications with polymer substrates in manufacturing are that the substrates are permeable, rather rough, and have a high coefficient of thermal expansion leading to adhesion and strain issues. In addition, they are incompatible with high-temperature annealing, which is needed for smooth indium tin oxide (ITO), and not as transparent or low cost as desired at around $10/m^2. Nevertheless, the ease of handling and compatibility with R2R processing make polymer materials a likely substrate candidate in the long term.

3.2.3 Electrodes and Current Spreading Layers

Standard OLED lighting devices have a bottom-emitting architecture, which requires a transparent electrode on the substrate side. ITO is currently the material of choice in rigid panels as it has satisfactory properties. The anode material must be transparent, conductive, and smooth. Further, the anode should have a high work function and withstand subsequent processing (not diffuse into stack). Further, the deposition methods used in fabricating the anode layer must be compatible with the substrate and any light extraction techniques employed. Though ITO offers satisfactory performance, it is brittle, somewhat costly, and requires high-temperature annealing steps to smooth the surface. Such processing would not be compatible with emerging polymer substrates or polymeric internal extraction layers. Though not yet adopted, several companies (including Arkema and PPG, with prior support from the DOE SSL Program) are investigating alternative materials with performance comparable to ITO and cost reduction potential. Prototype panels have been demonstrated with anode materials, including the following:

- Indium-free transparent conducting oxides (i.e. FTO, AZO)
- Nanowires
- Conductive polymer with wire grid
- Graphene

In choosing an anode material, transparency and conductivity are key concerns. For large-area OLED devices, uniformity of emission requires that the voltage drop across the panel is very small. Presently, there are no options for a transparent electrode material with high enough conductivity to prevent non-uniform emission in large-area panels. Strategies to overcome this issue are being explored, but presently the preferred approach is to use bus lines or grids to distribute the current over the emissive area of the device.

The introduction of auxiliary conducting grids leads to relaxed constraints on the conductivity of the transparent electrode material. European developers have suggested that polymer materials such as PEDOT:PSS could be used as combined electrode and HIL, when supported by a wire grid.

The use of printable metal inks is being explored to minimize waste in the formation of metal lines or grids. However, the conductivity of formulated metallic inks is three to five times less than the conductivity of the bulk metal, leading to greater optical absorption or higher aspect ratios for the printed lines. Silver inks are generating significant interest, but they are expensive. However, reports from a DOE-sponsored project by Electroninks and Solvay (ex-Plextronics) suggest that conductivity as high as 90% of that of bulk Ag can be obtained in inks at modest cost [35]. In a project funded by the DOE SSL Program, Cambrios demonstrated that their conductive Silver (Ag) nanowire ink offered transparency and conductivity comparable to that of ITO in OLED devices. Other metal inks such as copper are being investigated, but oxidation is a concern. However, Intrinsiq has demonstrated that oxidation can be controlled and has developed nanocopper inks with resistivity two to three times that of bulk Cu that are compatible with a variety of printing techniques. Both Ag nanowires and PEDOT/PSS can be deposited from solution.

Though in the very early stages of development, several teams are investigating the use of graphene as an alternative conductor. One effort is underway with Cambridge University's Graphene Centre and Plastic Logic, who are jointly investigating the use of graphene in flexible plastic electronics. There are significant issues with incorporating graphene into OLED devices. Most notably, the extremely thin nature of graphene layers leads to issues with conductivity, device uniformity, yield, and robustness.

Regardless of material choice, it is generally agreed that the electrodes used should be smooth. Roughness problems are exacerbated with the use of plastic substrates and low-temperature processing (that is required for the utilization of some light extraction enhancement methods). Avoidance of spikes is more important than minimization of the root mean square roughness, as the spikes cause leakage currents and shorting through the layers. The presence of wire grids or nanowires also can increase the possibility of shorting around the metal edges. Although surface polishing may help to ameliorate this problem, a simpler solution that is commonly employed is to use a thick HIL with conductivity enhanced through the inclusion of p-dopants.

3.2.4 Light Extraction Layers

Intensive research into ways to enhance the extraction of light from OLED panels has provided many potential solutions. However, almost all have proved to be difficult or expensive to manufacture over large areas. Various approaches to extraction enhancement include the development of external, internal, or cathode technologies. Most commercially available panels employ an external light extraction film. It is expected that to meet the DOE performance goals, symbiotic external and internal light extraction techniques will be necessary.

External light extraction approaches generally help to extract light trapped in substrate wave-guided modes. One method is to roughen the external surface of the transparent substrate. The surface of the glass can be modified during glass formation or after cooling by chemical or mechanical etching. Alternatively, a patterned layer of index-matched material can be laminated to the outside, for example, using micro-lens arrays. Similar films have been developed for several other applications. In general, the index of refraction of external light extraction layers needs to be lower than that of the substrate. Some low-index materials being explored include Teflon, aerogels, graded films of SiO_2 and TiO_2, and layers of SiO_2. Very good results have been reported for OLED light extraction by 3M, but the commercial availability of their films is not yet assured. External light extraction layers typically claim an extraction enhancement factor of 1.3 to 1.5, which is beneficial, but not good enough to meet efficacy targets.

The value of external light extraction films can be enhanced significantly through the use of substrate materials with a refractive index that matches that of the emitting layers. Such materials are available, but the cost is high. It is highly unlikely that these high-index materials will be obtained at affordable prices. Thus, internal structures may be needed to increase the amount of light that reaches the substrate.

Only recently have panel manufacturers begun to incorporate internal light extraction layers in their panel design. Internal light extraction approaches can be developed to extract light from wave-guided ITO/organic modes. One approach is the use of low-index grids on top of the ITO layer or a grid-patterned ITO layer used in combination with a conductive polymer. Such techniques have demonstrated an extraction enhancement factor of 1.7 to 2.3, but have not proven to be amenable to high-volume manufacturing due to the additional deposition and patterning steps required. Another internal light extraction approach is the incorporation of a scattering layer between the glass and ITO. This layer may comprise nanoparticles distributed in a polymer matrix with a substantially different refractive index, or may involve other scattering nanoparticles, such as Ag spheres or wires. Alternatively, the scattering layer may also serve as a replacement for the ITO layer in the case of the use of Ag nanowire anodes. Such layers could be deposited inexpensively by slot-die coating or jet printing. Such techniques show promise and could be scalable, but have not been adequately developed for use in manufacture. Challenges include issues with roughness, appropriate particle distribution within the matrix, and compatibility with subsequent processing steps. The DOE SSL Program has awarded funding to Pixelligent to explore graded internal light extraction structures based on ZrO nanoparticles.

Others have demonstrated the use of "buckle" structures to scatter light trapped in wave-guided modes. The non-planar topography of such structures may translate through the device to the cathode and thus further enhance the light extraction effect by reducing losses due to surface plasmon polaritons. Though effective in demonstrating an extraction enhancement factor greater than two, such non-planar structures introduce manufacturing challenges in terms of yield and control of uniformity due to the thin layer thicknesses and complex stacks often required in OLED structures, and the process of buckle formation may not be scalable. A different approach to reduce surface plasmon polaritons while extracting light from the ITO/organic layers is the use of ETL scattering layers adjacent to the cathode, such as was demonstrated by Novaled to achieve an extraction enhancement factor of 1.7. Cathode light extraction technologies are being developed in the laboratory making use of microstructures on the metal cathode, with reported gains of 100%, but these approaches are not yet well developed in manufacture.

Further work is needed in internal extraction layers and cathode light extraction technologies in order to achieve an extraction enhancement factor of at least 2 to 2.5. Such improvements will help to make efficacy targets more accessible. Additionally, if this level of extraction enhancement can be achieved with only internal extraction techniques, then the added value from an external extraction layer may not justify the additional cost.

The built-up light extraction structure (BLES) developed by Panasonic achieves an extraction enhancement factor of about 2.5 using just an internal extraction layer, as illustrated in Figure 3.3. Here, they use a thin layer of high-index plastic with microstructures imprinted on one surface and the transparent electrode deposited on the other. This film is laminated onto a normal glass substrate, with the structured surface facing towards the substrate, forming an "air gap" between the two to act as a low-index layer [36]. Using this technique, Panasonic has been able to achieve an efficacy of 133 lm/W in a 100 cm^2 device.

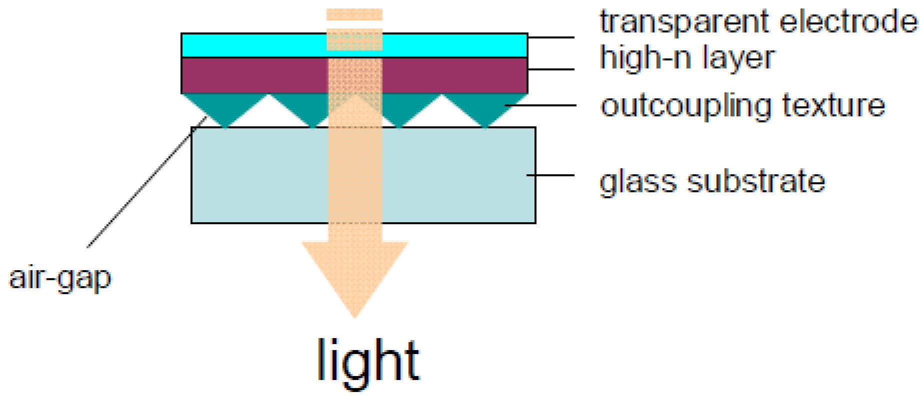


Figure 3.3 Internal Extraction Structure with Laminated Plastic Film
Source: Kazuyuki Yamae, et al., Panasonic Corporation

3.2.5 Integrated Substrates

High-performance panels with standard bottom-emitting architectures are built on substrates that may have the following components:

- Transparent substrate
- Light extraction structure
- Transparent conducting layer (anode)
- Current spreading approach

These composite structures are often referred to as integrated substrates. Most of the materials comprising integrated substrates are inorganic and the manufacturing challenges are very different from those of the active layers. Hence, the equipment requirements and processing know-how are also different, creating the opportunity for independent integrated substrate manufacturers within the supply chain. Such an approach benefits small U.S.-based companies pursuing OLED panel manufacture. If integrated substrates of high performance and low cost were available from external vendors, it would lower the start-up costs for a panel manufacture facility – saving on equipment, space, and personnel costs. Panel manufacturers could then focus on deposition of the stack and back-end processes.

Glass manufacturers are looking into the development of integrated substrates based on float glass. PPG, Guardian Industries, and Asahi Glass are all developing internal light extraction solutions using the incorporation of particles into the glass surface during or immediately following the glass fabrication. Nippon Electric Glass (which has already developed ultra-thin glass substrates and high index of refraction substrates for OLED lighting) and Saint-Gobain are also exploring such products under their new company called OLED Materials Solutions. Some companies are pursuing the development of complete integrated solutions including UCLA, Princeton University, and PPG, who are working with funding under the DOE SSL Manufacturing Initiative for this cause. UCLA and Princeton are working at solutions that are compatible with both rigid and flexible substrates. It has been emphasized by glass manufacturers that due to the high speeds and large widths at which glass production lines operate, a very large production volume would be necessary to make in-line manufacture of integrated glass substrates economic. Alignment of capacity and plans for growth throughout the supply chain would facilitate low-cost manufacture, but customization would be difficult. 3M is working on patterned external extraction layers as well as internal extraction layers. Such laminate films can be coupled to devices for a complete solution.

Collaboration between the substrate supplier and OLED manufacturers is critical to optimize interactions between internal extraction layers and the OLED stack, and to ensure compatibility of OLED deposition processes with the integrated substrates.

Requirements of an integrated substrate product include the following:

- Low cost (<$60/m2)
- Low effective sheet resistance (<1 ohm/sq)
- High-performance extraction layers to enable high EQE (>50%)
- Smooth deposition surfaces
- Compatibility with OLED stack deposition techniques

3.2.6 Encapsulation

Organic stack materials are so sensitive to water vapor and oxygen contaminants that very low levels of permeability are necessary, specifically 10^{-6} g/m^2/day for water vapor and 10^{-5} g/m^2/day for oxygen. Unfortunately, there are no other industries to draw from that have developed such high-performance, low-cost encapsulation schemes. All currently available encapsulation approaches are expensive, with encapsulation costs representing about 30% of the total OLED materials costs.

The current encapsulation approach for standard glass substrate devices is to cover the device with glass that is bound to the substrate with an edge seal. A cavity can be etched into the glass to accommodate the OLED device and a desiccant. DuPont's Drylox encapsulation system includes a desiccant that is printed on glass and a UV-cured epoxy seal. SAES Getters and Futaba are pursuing transparent desiccants, which could be beneficial for top-emitting structures. The edge seal material and the desiccant are expensive, so elimination of these materials can be cost effective. Corning uses a frit glass seal instead of epoxy. Here, a hermetic seal is formed such that a getter material is not needed, allowing for significant cost savings. This approach is applicable to smaller OLED devices, but issues are more complex for larger devices where the weight of the glass can compromise the edge seal.

Of course, this standard cover glass encapsulation approach is not compatible with flexible OLED devices using plastic or metal foil substrates. Several glass manufacturers are developing flexible glass sheets that could be used as lightweight, impermeable substrates and covers. Another avenue being explored for flexible substrates is barrier film technology.

Moving to barrier films is expensive and technically challenging. Yield and performance over large areas is a major concern as it is very hard to achieve a high level of protection over the entire region. Defect monitoring and control is difficult and time consuming, but essential. Other challenges include quality control, edge sealing, manufacturing efficiency, and maintaining sufficient transparency of the barrier film and plastic substrate combined.

Barrier films typically comprise alternating layers of organic and inorganic materials. Metal oxide and polymer layers are stacked, making a tortuous path for contaminants to diffuse through to reach the device. To achieve high-quality barriers, slow deposition of smooth metal oxide layers is ideal. This is time consuming and costly, with a price of around $50/m^2. Some companies are looking into rapid atomic layer deposition techniques for barrier films to overcome this issue. Companies involved with multi-layer barriers include Vitex Systems, Appliflex, 3M, GE Plastics, and IMRE. Samsung purchased Vitex Systems for their multi-layer barrier technology, which claims 10^{-6} g/m^2/day for water vapor. Manufacturing of this technology is slow, complicated, and expensive, but there is currently no better alternative. UDC is working on a single-layer barrier technology, which consists of a hybrid organic-inorganic encapsulant called UniversalBarrier. Though they need to scale up this technology, they are currently working with ASU's Flexible Display Center and industrial partners to evaluate its effectiveness. Barrier films are currently produced with batch processes, but roll-to-roll processing of barrier films would be useful in the future for costs to come down.

3.3 OLED Manufacturing Equipment

As described in Section 3.1, the traditional approach to manufacturing OLED panels has been to form all the internal layers onto rigid substrates using vapor deposition under high vacuum conditions. These techniques are discussed in Section 3.3.1, while alternative approaches using solution processing and roll-to-roll handling are outlined in Sections 3.3.2 and 3.3.3. The final critical step is encapsulation, as described in Section 3.3.4.

The capital cost of the equipment used for manufacturing OLED lighting panels is very high. The amount is strongly dependent on the size of substrate used. While pricing is uncertain as high volume lines are not yet in use, the costs can be estimated as shown:

- $50-$100 million for "Gen 2" at size 370 x 470 mm (0.17 m^2)
- $150-$300 million for "Gen 5" at size 1,100 x 1,300 mm (1.4 m^2)
- $300-$600 million for "Gen 8" at size 2,200 x 2,500 mm (5.5 m^2)

With traditional manufacturing techniques, approximately half of the capital cost is associated with deposition of the organic layers and the cathode. The cost of patterning equipment for integrated substrates is substantial, but this investment can be borne by the substrate supplier, rather than the panel maker. Part of the reason for the high cost is that the structure of high-performance OLED lighting panels is relatively complex:

- Double or triple stacks help to lower the current density and increase operating lifetimes.
- Separate emitter layers lead to higher efficacy and stability.
- Adding metal grids to transparent electrodes improves the uniformity and reduces ohmic loss.
- Extraction enhancement layers are needed to minimize light trapping inside the panel.
- Very effective barriers must be deployed to prevent ingress of water and oxygen.

The linear production lines constructed by LG Chem and First O-Lite employ around 20 deposition chambers, each of which can cost over $1 million at Gen 2 size. Reducing the number of organic layers should lead to reduced capital costs, but more effective light extraction structures would be needed to compensate for lower efficacy of the emitters.

3.3.1 Vacuum Processing Equipment

Equipment costs are a major component of the total OLED cost of manufacture. The cost of ownership needs to be reduced by lowering capital costs and increasing the throughput and yield. Some equipment can be eliminated through OLED design simplification and advancements. For vacuum processing equipment cost reductions, innovations are needed in the following areas:

- Patterning for wire grid formation
- Simplification of device architecture
- Cost-effective, small-scale production facilities
- Reduced cycle times

Sputtering has been the preferred technique for the first electrode, while the organics and second electrode are usually deposited by evaporation. Each of these techniques leads to a layer of material across the whole work piece. Some degree of patterning is needed in lighting applications, although this does not have to be accomplished with the fine resolution needed in displays.

Photo-lithography has been used to pattern the anode structure, with its sheet of transparent conductor (TC) supplemented by a wire grid. This is time-consuming and expensive. Alternative ways to remove unwanted TC materials from around the edge of each panel include laser ablation and such equipment is readily available. Another approach is to use a relatively crude mask to define the area within which the TC materials are needed. Neither of these solutions is optimal for forming the grids, since metal is needed over a small fraction of the total area. Techniques that do not rely on subtraction patterning, such as stamping or printing, could help eliminate unnecessary expense.

LG Chem and other companies have often stated that the most straightforward way to reduce the cost of vacuum deposition is to move to larger substrates, such as Gen 5 or Gen 8. One reason is that the production capacity scales more rapidly than the anticipated cost. Another is that the material utilization improves, since the ratio of useful substrate area to unproductive edge area increases. Appropriate equipment from companies such as Aixtron, Applied Materials, and Sunic Systems has been tested in Korea and in Europe. However, it will be many years before the market is developed sufficiently to justify the high levels of production that would come from even a single line of these sizes. This has led some manufacturers, such as Trovato Manufacturing, to prioritize introducing innovations that can lead to manufacturing cost reductions without scaling up the production process.

Reducing the cycle time is one route to lower cost of ownership for manufacturing tools. The traditional cycle time for display manufacturing is approximately 90 seconds, whereas that of most existing lighting lines is longer. The commercial success of OLED lighting could be enhanced significantly if the cycle time could be reduced to below 60 seconds. This drove Moser Baer to explore small-substrate techniques similar to those used in the optical disk industry. Although there is no evidence yet that high-performance OLED panels can be manufactured in such short times, this approach is being pursued by several manufacturers.

One problem in accomplishing this with the standard evaporation technique is that rapid deposition requires high evaporation temperatures. Intricate molecules become fragile at high temperatures and so the challenge is to find materials that are exceptionally stable or to restrict the time the source gases remain at high temperatures [37]. The deposition rate also influences the film structure and surface morphology, with lower deposition rates typically producing smoother, higher quality films. The typical layer thickness for organic emitters is 10 to 30 nm. Thus, deposition rates of around 1 nm/s are needed to achieve the desired cycle times. However, the transport layers are often much thicker to reduce losses through plasmon excitation at a metal electrode and to guard against shorting at transparent electrode structures. Thus, faster deposition of these layers may be needed. It is possible that transport materials may be more tolerant of high temperatures than the more intricate emitters. However, many developers have suggested that the use of wet deposition techniques, such as slot-die coating, may be more appropriate for some of the transport layers. The challenge then is to minimize the drying time.

A second challenge is to reduce the time lost in moving the substrate from one tool to the next. This has been part of the rationale for the use of R2R equipment. However, the development of R2R tools appropriate for high-performance organic materials (and the materials themselves) has been slow and they have not yet been used in commercial production, as discussed in Section 3.3.3. The alternative is to use sheet processing with a linear configuration in which the substrates can move smoothly from each stage to the next. The fact that accurate registration is not needed in lighting applications makes this approach more feasible than for high-resolution displays. An alternative approach being proposed by equipment manufacturers for stationary substrates is to use deposition tools with multiple sources so that several layers can be added in a single stage.

A good example of the status of organic deposition equipment for lighting is provided by the pilot line sponsored by the Ministry of Knowledge Economy in Korea [38]. The substrates move steadily through 1,000 mm x 1,200 mm deposition chambers at a speed of 1.4 m/min, consistent with a 60s cycle time. A 50 nm layer of a relatively simple organic material (Alq3) was deposited from a linear source at a rate of 2 nm/s with high uniformity (±1.3%). However, it is not clear whether such good performance could be obtained with the more delicate materials that achieve higher luminous efficacy.

Aixtron continues to improve the performance of their OVPD equipment, in which organic material is carried from the source to the substrate in a rare-gas mixture. They have demonstrated significant cost reductions in a Gen 3.5 system (600 mm x 720 mm) by:

- Reducing the gap from shower head to substrate to 200 mm
- Reducing edge losses by chamber design and surface heating
- Shortening the exposure of material to high temperatures

In January 2014, Aixtron announced a joint venture with Manz AG to demonstrate the operation of OVPD technology at the Gen 8 scale (2,300 mm x 2,500 mm).

3.3.2 Solution Processing Equipment

Though vapor deposition is the current and most promising near-term approach, development of solution deposition techniques and materials is underway. In the long term, as performance improves, these methods may allow for substantial cost reductions as materials utilization can be much more efficient using solution deposition techniques. Many prototype panels are being produced that feature one or more solution-processed layers. These hybrid devices are the next step towards completely wet-processed devices. The viability of using solution deposition for the emitting layers has been demonstrated by companies developing these materials, such as Sumitomo Chemical, Mitsubishi/Pioneer, and Konica Minolta.

Rapid deposition of both organic and inorganic materials can be accomplished by forming inks in which the desired material is trapped temporarily in a solvent. The inks can then be applied to the substrate by jetting or by contact printing. The solvent is then removed through a drying process.

Two versions of jetting have been explored with organic materials and metals. The use of 2-D patterns can be formed through ink-jet printing (IJP), in which the ink forms droplets as it leaves the printer. This method is often used in making OLED displays with 2D array of small pixels. In nozzle jet printing, the ink flows continually and stripes can be formed more uniformly.

The application of IJP for depositing OLED materials was pioneered by Epson and CDT/Sumitomo, but tools are now available from several suppliers, such as Kateeva, Epson, and Fujifilm Diamatix. Sumitomo have set a target date of 2015 for the commercial introduction of lighting panels, based upon IJP of their polymer-based materials. Nozzle printing equipment has been adapted by Dai Nippon for OLED materials from DuPont. This technique was used by DuPont Displays to develop color tunable and illuminance variable OLED panels in a project supported by the DOE SSL Program. Although Samsung has been testing the nozzle printing approach, no schedule has been announced for adoption in commercial products.

Contact printing methods that have been used for OLEDs include slot-die coating, screen printing, and gravure printing. Although slot-die coating has traditionally been used to create a uniform layer across the whole substrate, it has been recently demonstrated that multiple panels can be formed, with no deposition between the individual panels, as shown in Figure 3.4.

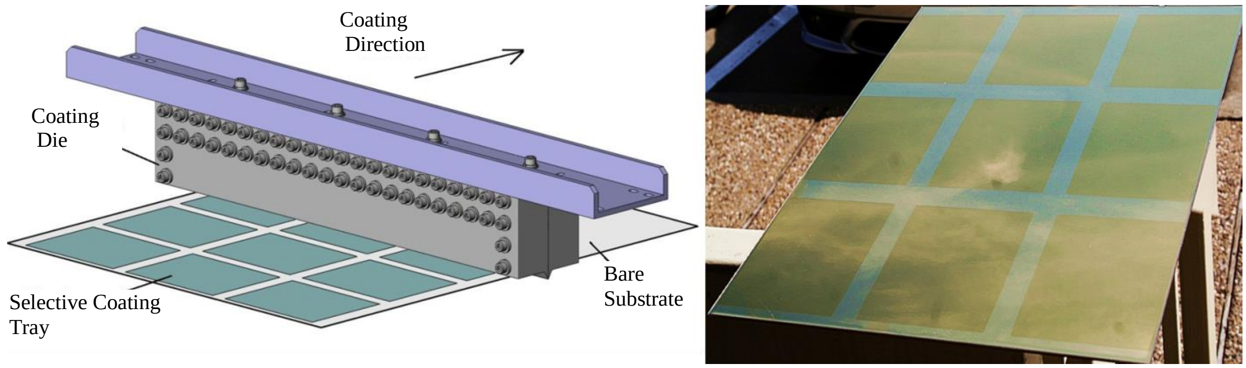


Figure 3.4 Slot Coater Adapted for Coarse Patterning
Source: Robbie Charters, nTact, 2012 Flexible Electronics & Displays Conference & Exhibition, Phoenix

The quality of the film can be optimized by varying the thickness of the slot and the size of the gap between the slot and the substrate. Throughput is governed by the rate at which the substrate moves past the slot. Speeds of 100 mm/s and higher have been demonstrated for both organic materials and inks containing silver nanowires. Tools that are specially designed for this application are available from suppliers such as mBraun, nTact, and Tazmo.

Since even relatively thick coatings can now be deposited rapidly, the rate-limiting step is often the solvent drying process. Although some experiments have been carried out with UV-curable materials, thermal drying is still the preferred approach. Several minutes may be required to remove all of the solvent. With sheet-to-sheet handling, the process times can be matched by using long ovens or by stacking substrates. In R2R systems, the web can be looped between several rollers within the oven.

Many of the traditional printing techniques have been adapted for the deposition of the anode structures and internal extraction layers. At the DOE Manufacturing Workshop in 2014, Rolith demonstrated a new approach, using "Rolling Mask Lithography", which employs a phase-shift cylindrical mask and can be used in a roll-to-roll line [39]. This method offers the following:

- Resolution to 150 nm with i-line exposure
- Throughput to 1 m^2/min
- Cost as low as \$5/m^2
- Scalability to Gen 8 (2,200 mm x 2,500 mm)

A prototype tool of size 1,000 mm x 300 mm has been built in cooperation with SUSS MicroTec AG and tested on rigid substrates.

3.3.3 Roll-to-Roll Processing Equipment

R2R processing could be a potential avenue for low-cost production and will soon be tested in commercial production. Konica Minolta and Sumitomo Chemical have recently reasserted their view that R2R processing will provide an economic route towards the manufacture of OLED lighting panels. Konica Minolta prefers to use slot-die coating to deposit the small-molecule solution processed organic layers. Although they demonstrated panels with efficacy of 52 lm/W using a simple four-layer structure back in 2010 (in collaboration with GE), improved performance has not yet been reported and Konica Minolta is producing their current Symfos panels by vapor deposition onto rigid sheets using the Philips line in Aachen.

Konica Minolta is constructing a R2R OLED lighting production line to mass produce flexible panels on plastic substrates. The target is to invest $100 million in the facility, which will have a monthly capacity of a million panels per month (both white 150 mm x 60 mm, and color-tunable 50 mm x 30 mm panels).

However, the viability of the R2R approach seems to depend on the simplification that could result from the design of high-performance panels with fewer layers. This has been the traditional approach with polymer molecules, but the performance of these materials still lags behind that of small molecules deposited in vacuum. This provides incentive to develop simple structures for solution-processed small molecules, such as that suggested by Hitachi [40].

A major obstacle to implementation of roll-to-roll processing on plastic substrates has been the unavailability of effective barrier films to prevent ingress of oxygen and water. Although there have been many laboratory demonstrations of such films, the production of defect-free films in high volume at affordable costs has not yet been achieved. A possible alternative route is through the use of ultra-thin glass. Rolls of glass with thickness down to roughly 50 µm are now available from several vendors. In November 2012, the Industrial Technical Research Institute in Taiwan announced that they had completed a full R2R processing line using 100 µm glass from Corning and had applied the line successfully to the manufacture of touch panels. OLED lighting is one of the intended applications for this technology.

R2R web handling is compatible with both vapor deposition and solution processing. Gateways have been available for several years to allow the web to flow between tools at widely different pressures and have been used successfully in OLED fabrication at both Fraunhofer COMEDD and GE Lighting.

3.3.4 Encapsulation Equipment

The encapsulation process to form edge seals in OLEDs with a rigid substrate and cover consists basically of three steps:

- Surface cleaning
- Dispensing of the epoxy seal or frit
- Curing of the sealant material

Although the surface of the substrate is often cleaned thoroughly before processing begins, additional steps may be needed to remove material that has been deposited near the edge during the formation of the OLED. Laser ablation is commonly used, but care must be taken to ensure that the debris is not trapped in the panel during encapsulation.

Although assuring the integrity of the seal is extremely challenging in terms of the selection of materials, the dispensing and curing steps seem similar to those required for other electronic applications. UV curing is commonly used with epoxy materials and laser sealing with glass frit. As noted above, frit sealing has been very successful in small OLED displays using two sheets of matched borosilicate glass, but extension to large sizes is challenging. This approach also may not be appropriate when metal foils are used as covers to reduce the overall thickness of the panel.

SAES Getters has been amongst the pioneers in the development of dessicants and edge seals for OLED panels. Their materials can be dispensed in many ways, including lamination from drums, extrusion from pellets, needle or jet dispensing, and blade coating.

The development of effective thin-film encapsulation could reduce the thickness and weight of glass-based OLEDs as well as enabling the production of flexible panels. Equipment to form multi-layer coatings with alternating inorganic and organic layers was available from Vitex before their acquisition by Samsung. Research to provide more reliable ways to form the inorganic layers that are prone to pin-holes, cracks, and other defects is underway at several companies. For example, Beneq has reported substantial progress in the development of production machines for atomic layer deposition (ALD). ALD produces excellent films at relatively low temperatures (compatible with plastic substrates), but is a relatively slow deposition process. Beneq has demonstrated a fully automated Gen 2.5 system capable of handling 35 substrates with a total available cycle time of 4 minutes. A prototype roll-to-roll system with a 500 mm web has been operating since January 2013 and has achieved thickness control to ±2% and deposition rates for 18 nm Al_2O_3 films of 1 m/minute.

Veeco has also developed equipment for rapid coating by ALD, but this has yet to be tested in high-volume production. Applied Materials and PlasmaSi are pursuing more traditional plasma-enhanced chemical vapor deposition (PECVD) methods.

3.4 OLED Panel Manufacturing

In many ways, the design of panels for OLED lighting is similar to that used by LG Display in OLED panels for displays. The following are the main differences:

- The array of thin-film transistors is not needed due to the absence of micro-scale pixels.
- Color filters are not needed to separate the panel into red, green, blue (RGB) pixels.
- Polarizers are not needed to control reflected light.
- Conducting structures are typically needed to ensure uniformity across the panel.
- Efficacy targets are higher.
- Lumen maintenance requirements are higher.
- Higher luminance is required for lighting.
- Color balance is more important than color saturation.

Further discussion on design issues can be found in the 2014 MYPP[m].

These considerations have led both LG Chem and First O-Lite to adopt the vertically stacked tandem structures that were developed by Kodak. The drive voltage of 9.5V in the second generation of the Philips GL350 panel also suggests that a triple stack is used. Further, Philips takes advantage of the increased luminance afforded by vertically stacking devices as emphasized in their Brite FL300 OLED panel, which has a 100 mm x 100 mm emissive area producing 300 lm with a drive voltage of 19 V at max brightness (9,000 cd/m^2). They report efficacy of the 3000K device to be >50 lm/W and lifetime to be 10,000 hours.

Figure 3.5 shows an example of a tandem structure illustrated by First O-Lite wherein two sets of multiple emission layers are stacked on top of one another and are separated by one or two charge generation layers. Light trapping is reduced through the inclusion of internal and external extraction structures (IES and EES). This approach significantly improves lifetime and light output, but may require as many as 20 layers in the organic stack.

Another design consideration leading to the manufacture of vertically stacked devices is color-tunability. Fraunhofer COMEDD has demonstrated color tunability using individually controlled, vertically stacked OLED emitters. Typically, color tunability is achieved by patterned strips, such as in Verbatim's Velve panels or the Acuity/UDC panels developed with support from the DOE Small Business Innovation Research (SBIR) program.

[m] The 2014 SSL MYPP is available at:
http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mypp2014_web.pdf.

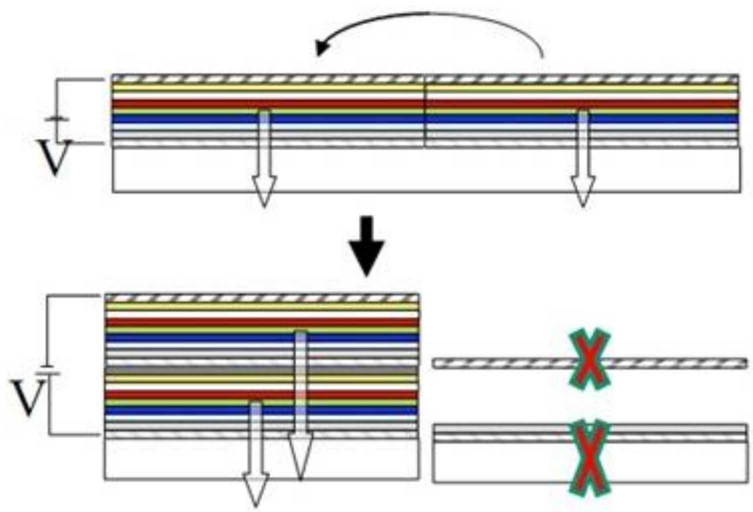


Figure 3.5 Tandem OLED Architecture
Source: First O-Lite, Inc.

The manufacturing techniques used by LG Chem and First-O-Lite are similar and will be regarded as the "base process," which comprises the following steps:

- Display glass of thickness around 0.7 mm is cleaned and surface treated to ensure smoothness.
- Internal scattering layers are added using undisclosed proprietary techniques.
- Wire grids and ITO layers are deposited by sputtering and patterned by photolithography to form the anode structures.
- The anode structures are cleaned and/or surface treated in a plasma to ensure smoothness.
- The organic layers are formed by evaporation under high-vacuum conditions with an in-line configuration of deposition chambers.
- The cathode is deposited by evaporation.
- The stack is covered by a thin layer of desiccant and edge sealants.
- Display glass is added as a cover and the sealant is cured.
- The external extraction film is laminated onto the glass substrate.
- Testing and burn-in are completed to protect against early failure.

Both companies are using substrate sizes of about 370 mm x 470 mm with target cycle times of approximately two minutes. LG Chem is performing the whole process in a two-story building with a total clean-room space of around 40,000 m^2. However, it is possible to outsource the first three steps, which accomplish substrate preparations.

Since it is uncertain that continuation of this approach will lead to the desired cost reductions, the remainder of this section is devoted to a comparison of alternative manufacturing strategies. These cost-reduction strategies rely on improvements in the following areas:

- Process integration
- Process control
- Materials utilization
- Manufacturing yield

3.4.1 Process Integration

Although the optimization of individual process steps is important, there is significant interplay between the different components of an OLED panel that need to be taken into account when choosing manufacturing techniques. Also, a single line for the whole manufacturing process is not needed, and some of the work could be outsourced. This is particularly attractive to small companies and may ensure the full participation of manufacturers with specific capabilities.

The natural division in the manufacturing process is between the construction of the underlying structures, which mainly consist of inorganic materials and the formation of the organic stack. For example, since the opportunity for substantial profit margins in the supply of substrates is limited, most glass companies are keen to provide integrated substrates with extraction enhancement layers and anode structures.

Since the deposited organic materials are extremely sensitive to oxygen and water vapor, encapsulation is usually performed in-situ as soon as possible after the second electrode is added. However, an alternative would be to deposit a temporary protective layer and to complete the encapsulation in a separate facility. The substrate supplier may also wish to be involved in encapsulation, since the optimal sealing process may depend on the properties of the materials used in the substrate and cover.

3.4.2 Process Control

There has been substantial disagreement within the OLED community about the difficulty of assuring control over the intensity and color of the emitted light. Optimists have assumed that the diffuse nature of the OLED light source and the smoothness of the emitting layers will mean that the need for control will be less than for inorganic LEDs and that binning can be avoided.

Experiments carried out by UDC with DOE support have helped to establish the acceptable variations in the thickness of organic layers and in doping fractions. The results seem to lie within the levels of control that equipment manufacturers have claimed, both with respect to spatial and temporal changes. However, comparison amongst multiple panels at shows and after installation by customers reveals noticeable color variances between panels, suggesting that more work is needed.

Monitoring of temporal variations in the deposition rate is most easily accomplished using quartz crystal microbalance (QCM) placed in the chamber but away from the substrate. Although QCMs have been used for several decades, considerable modification has been required for them to operate reliably over many days at high deposition rates. Suitable measuring systems are now available from companies such as Colnatec, but this approach does not give information about the spatial variations in deposition rates. By working with the Fraunhofer COMEDD, Laytec has demonstrated that in-situ measurements of the thickness of organic layers can be measured using reflectometry. Accurate measurements can be deduced using light of a single wavelength only if the thickness exceeds the wavelength, so the spectral variation of the reflectance may provide the key in OLED applications.

Because of the very low thickness of OLED layers and the susceptibility of the organic materials to oxygen and moisture, particulate control is essential throughout the manufacturing process.

The availability of cost-effective techniques for detecting small particles would be of major benefit to yield improvement.

3.4.3 Material Utilization

Considerable progress is being made in increasing the utilization of organic materials. In the conventional vapor deposition approach, as shown in Figure 3.6, this has been accomplished by doing the following:

- Replacing single-point sources by linear or planar sources (e.g., shower heads)
- Heating the walls of the deposition chamber and supply lines
- Increasing the ratio of substrate size to the area of the deposition chamber
- Reducing the distance from the source to the substrate

Sunic has reported utilization rates greater than 40% in Gen 2 equipment and over 60% in Gen 5 tools. By reducing the source to substrate distance from 250 mm to 150 mm, they have achieved a utilization rate of 79%, while suffering only a small deterioration in uniformity (from ±1.3% to ±1.8%).

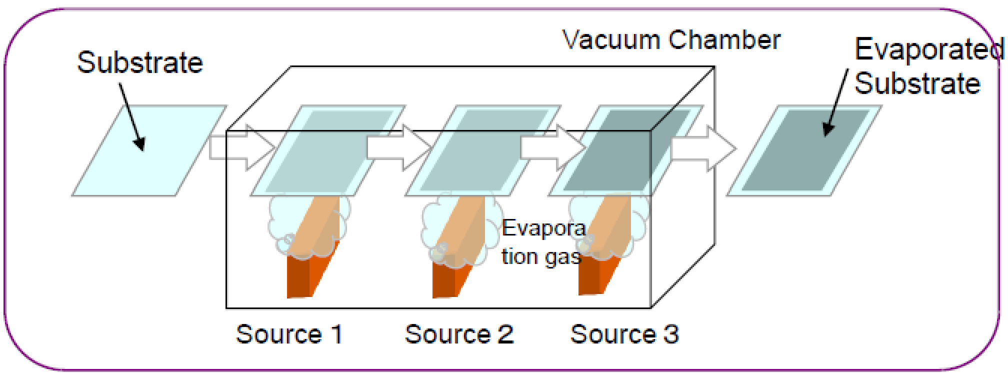


Figure 3.6 Schematic of In-Line Evaporation Process
Source: Takuya Komoda, Panasonic Corporation, SEMICON Europa, 2012, Dresden

Losses to the chamber walls and supply tubes can be reduced by heating the walls. By evaporating from a linear source into a chamber with heated walls, Panasonic has achieved 70% material utilization on a substrate of only 200 mm width. The substrates move steadily across the sources and a valve is used to stop the flow between panels.

The materials utilization of solution-processed materials has traditionally been higher than that of those deposited in vapor. However, the gap is closing. In a design analysis of a Gen 8 (2,200 mm x 2,500 mm) nozzle printing tool, DuPont has confirmed that utilization at over 90% can be achieved with a wide range of choices of nozzle and head configurations. However, they suggest that the optimal balance of cost and performance is obtained with a utilization of 76%. The slot-die coater supplied by nTact is designed to give 83% utilization for Gen 2, 93% in Gen 5, and 96% in Gen 8.

Regardless of the manufacturing method, optimizing the layout of the panels on the substrate is critical to reducing the effective cost of light-emitting devices. In the panels on the market today, the width of the edge areas from which light does not emerge varies between 10 and 25 mm, out of a total dimension of less than 150 mm. When multiple panels are produced from a single substrate, gaps need to be left between each panel and around the edge of the substrate. These considerations are particularly important when panels are small and currently mean that less than 60% of the total substrate area is used to produce light. The production of panels with non-rectangular shapes will increase the ratio of non-productive area.

3.4.4 Manufacturing Yield

Manufacturing yields are closely guarded by all OLED manufacturers. At a press conference in April 2013, DisplaySearch estimated that the yield of 55” OLED TVs was around 10%. Although some of the problems arise in the formation of the TFT back-plane in display applications, the need to deposit OLED stacks for lighting on top of light extraction layers and wire grids also leads to substantial challenges.

At least one leading producer of OLED lighting panels has identified shorting as the major contributor to low yields. Irregularities in the structures below the ultra-thin OLED layers can lead to enhanced currents and hot-spot formation. Particulates must be avoided at all stages. Conducting particles of even 10 nm in diameter could be disastrous. It is extremely difficult to detect particles optically at dimensions that are less than approximately 200 nm and surface profilometry would be too time-consuming and expensive to be used in production. Cleanliness is therefore critical, whether processing is done under vacuum conditions or at higher pressure. To help planarize the deposition surface, a thick HIL or HTL is often used for electrical short prevention. The primary purpose of this layer is to facilitate hole injection into the device. However, if the material is transparent and conductive enough that the drive voltage of the device is not negatively changed, a thicker layer than needed for charge transport can be deposited to smooth out the rough anode surface. Solution HILs are a popular choice.

Undetected shorts represent a major threat to panel manufacturing. Even if only one panel in 10,000 had to be returned due to shorting in early operation, the damage to the reputation of the producer could be unacceptable. There appears to be no method to identify panels that may be susceptible to early shorting, except by burning the panel at the factory for many hours. This is also a time-consuming and expensive process. Thus, developing a technique to scan panels for potential shorts would be valuable.

3.4.5 Manufacturing Cost Model

The overall OLED cost targets in previous DOE Roadmaps have been set mainly by market expectations. The division of the total cost between the different components was set using community assessments of aggressive, but plausible reductions. In several editions the schedule for achieving the targets has been delayed, but the market imperatives remain. The daunting nature of the challenge is well illustrated by calculations made by Barry Young (of the OLED Association) as part of a DOE SSL Manufacturing Project and presented at the Manufacturing Workshop in 2014 [41].

The OLED Association cost model simulates the way a manufacturer would accumulate the costs by charging the maximum depreciation possible in the early years using a declining balance approach. Materials and components are assumed to decrease in price based on historical experience plus price breaks for volume increases over time. There are a range of configurations that a manufacturer could employ in terms of the stack architecture. In this model a two-color phosphorescent approach was used, which included a red/green combination and a blue layer to achieve white. The model does not forecast performance but it is expected that efficacy, lifetime, luminance, color temperature, CCT, CRI, and uniformity will continue to improve from their current performance levels as outlined below. The bottom substrate is assumed to contain the internal and external light extraction layers, and the grid if necessary. A glass cover plate is also assumed. The electronics include drivers and power supplies. Cumulative yields are forecasted to increase from ~55% in 2015 to ~75% by 2020. Manufacturing is based on Vacuum Thermal Evaporation (VTE) using a batch process (not in-line) with glass-to-glass encapsulation.

Figure 3.7 shows the modeled cost of producing 6" panels on a Gen 5.5 substrate (1,300 mm x 1,500 mm). The cost decreases steadily as production increases from 5,000 to 100,000 substrates per month, which is assumed to occur between 2015 and 2020.

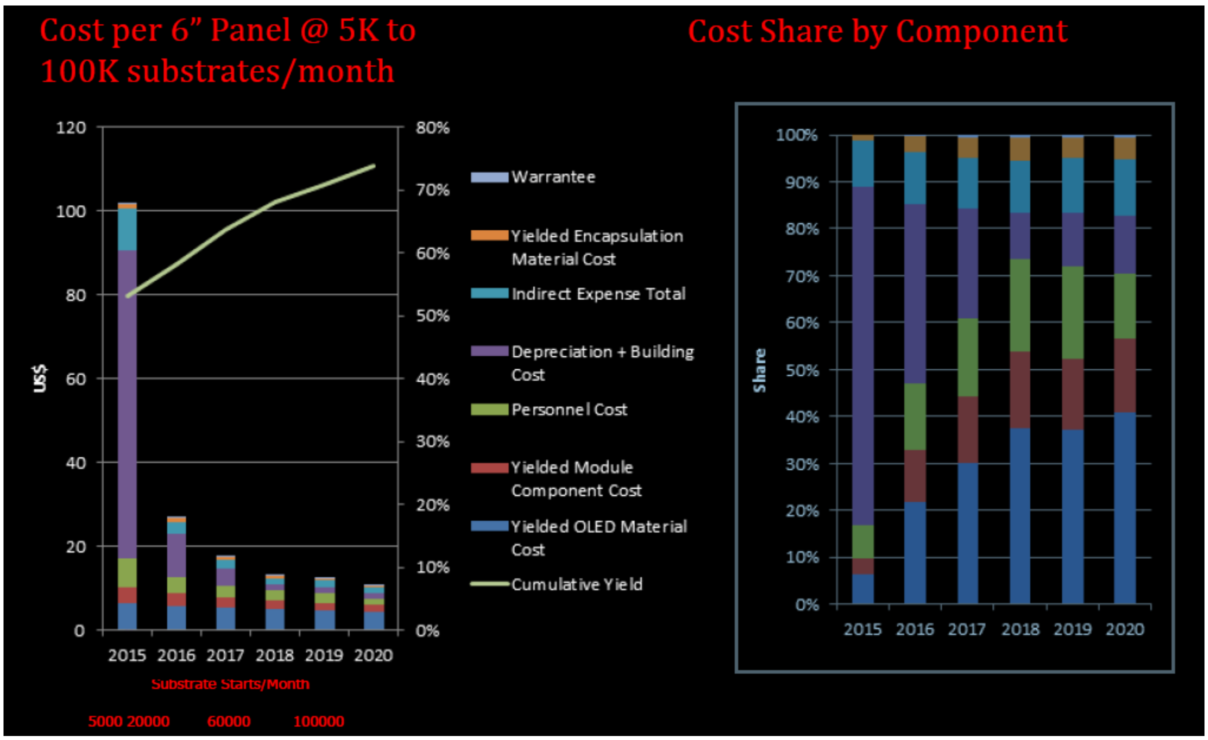


Figure 3.7 Anticipated Cost of 6" OLED Lighting Panels Using Traditional Techniques: (a) absolute costs, (b) cost share

Source: Barry Young, OLED Association, DOE SSL Manufacturing R&D Workshop, 2014, San Diego

To place these results in context, each substrate would enable the formation of 72 panels. The yielded output from a single line would increase from 200,000 panels per month in 2015 to 5 million panels per month in 2020. Assuming a luminance of 10,000 lm/m^2, each panel would produce around 200 lm, so that the scaled production cost would fall from \$500/klm in 2015 to \$60/klm in 2020. The fact that LG Chem is willing to sell panels at \$200/klm produced from smaller substrates suggests that they may not be recovering the complete manufacturing costs and are writing off the cost of the line. This analysis suggests that the added cost of producing each extra panel on an underutilized line is about \$100/klm.

Even if one does not allow for maintenance or unscheduled stoppages, the final assumption of 100,000 starts per month implies a cycle time of less than 30 seconds. Achieving this will be difficult with traditional methods, unless multiple tools are used for the slowest steps. The resulting cost of $60/klm would still be over the goal of $24/klm set in Table 1.6 and the price anticipated for LED luminaires in 2020.

An independent assessment of the cost of traditional sheet-to-sheet vacuum deposition processing was offered at the same workshop by John Hamer of OLEDWorks [34]. He estimates that for a nominal cycle time of 1 minute and capital cost of $75M, the depreciation charge for a Gen 2 line is $250/m^2 (with 5 year straight-line depreciation with 80% glass pattern usage and 80% uptime). For a Gen 5 line with cost of $200 million and the same cycle time, the charge would be $80/m^2. Table 3.1 then presents a scenario for depreciation charges that would be acceptable within the total cost framework presented in Table 1.6, assuming that the transition from Gen 2 to Gen 6 occurs between 2016 and 2020.

Table 3.1 Estimated Cost of Panels Produced by Traditional Methods (OLEDWorks)

	2013	2014	2016	2020	2025
Substrate Area (m^2)	0.17	0.17	0.17	1.43	1.43
Capital Cost ($M)	75	75	75	200	200
Cycle Time (minutes)	3	2	1	1	0.5
Depreciation ($/m^2)	750	500	250	80	40
Total (unyielded) ($/m^2)	1,500	1,200	700	180	80
Yield of Good Product (%)	25	40	70	75	80
Total Cost ($/m^2)	6,000	3,000	1,000	240	100

The major difference between the two cost models is that the OLEDWorks cost model (Table 3.1) assumes that the line is being used at capacity in full production mode (584 hours per month). This is unrealistic at the moment, because the market demand is too small to absorb such a level of production, even from a single line. The OLED Association cost model (Figure 3.7) assumes a gradual ramp-up of production, but in this case, the calculated cost of depreciation cannot be recovered.

OLEDWorks believes that there is a solution to this dilemma and that the depreciation targets can be reached with much smaller throughput levels using less expensive equipment. In order to achieve the total costs in Table 3.1, OLEDWorks suggests that the line capital cost should be $100 for each m^2 of annual production of finished product, leading to depreciation charges that would be only $20/m^2 or $2/klm. Such a production line would allow for the possibility of affordable panel pricing, customizable products, malleable fabrication lines, and reasonable supply. The DOE has recently awarded OLEDWorks funding that supports the development of this strategy. Though the feasibility of this approach is yet to be demonstrated, it holds promise, especially for North American manufacturers that have no external support to mitigate investment risks.

3.4.6 OLED Luminaire Manufacturing

Integrating OLED panels into functional luminaires represents an entirely new manufacturing challenge. Unlike LED luminaire manufacturing, which can draw upon manufacturing expertise from conventional luminaire manufacturing, consumer electronics manufacturing, and semiconductor manufacturing, there is no clear analog for OLED luminaire manufacturing. New approaches and platforms must be developed for the manufacturing of the mechanical structure of the luminaire and the electrical connection of the panel within the luminaire. These new approaches should be flexible to allow for the production of a range of lighting products for a range of lighting applications. Currently, the available OLED luminaires rely on custom, hand-assembly, which is not feasible to reach the projected manufacturing costs and desired production levels.

So far, OLED-based luminaires have been produced mostly for demonstration purposes rather than for sale in high volume. While these luminaires show what is possible with OLEDs (see Figure 3.8), they also demonstrate that there is a lot to learn regarding efficient, low-cost OLED luminaire manufacturing. Factors impacting the wider adoption of OLED luminaires include the need for improvements in test and performance standards, driver interfaces, measurement techniques, and mechanical structures.

Figure 3.8 Examples of OLED Luminaires: a) the Acuity Lumen Being interactive lamp b) a designer OLED luminaire by OSRAM and c) the LG Chem fixture using flexible OLED panels
Source: Acuity Brands, OSRAM, and LG Chem

The development of OLED drivers has lagged significantly behind that for inorganic LEDs. At the 2014 SSL Manufacturing Workshop, Innosys showed how OLED driver design can benefit from much of the LED work, with respect to power factors, control of EMI and total harmonic distortion (THD), safety precautions, network compatibility, and some dimming issues, but specific attention to OLED requirements is critical. For example, color control and failure mechanisms can be very different in OLED systems. In the first stage of a DOE SBIR program, Innosys has demonstrated efficiencies up to 92%, with high power factor and low THD in a driver enabling remote control of an OLED desk lamp [42].

Mechanical and electrical connections for the panels also need development. The Trilia family (see Figure 3.9) introduced by Acuity demonstrates one way to allow a high degree of customization of products from a few basic building blocks with uniform connections.

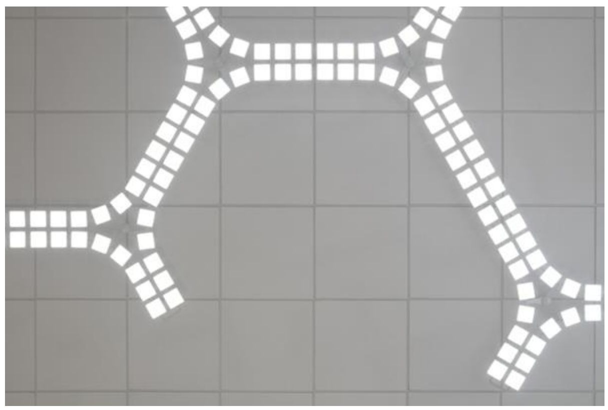


Figure 3.9 Trilia OLED Luminaire by Acuity Brands
Source: Acuity Brands

An important concern of LED luminaire manufacturers is to control the distribution of light emerging from the fixture. Most OLED panels emit light over a complete hemisphere, with a distribution close to Lambertian. This is far from ideal in many applications and could lead to unacceptable glare from ceiling or wall fittings. So the addition of optical elements to direct the light in a more appropriate fashion may be required. This aspect has been addressed only minimally in the available luminaires.

Research into OLED luminaire manufacturing and assembly is only in its infancy. Considerable work is required to find high-performing, cost-effective ways to integrate panels into luminaires. Inevitably, OLED luminaire manufacturers will need to address issues related to transitioning OLED from a light source to lighting products. Similar to the transition that LEDs faced, issues with drivers, controls, thermal management, light distribution, and mechanical mounting of OLED panels will need to be addressed.

3.5 OLED Manufacturing Priority Tasks for 2014

DOE identified the following priority OLED manufacturing R&D tasks based on discussions at the Manufacturing Workshop and post-workshop teleconference.

M.O1. OLED Fabrication Equipment: Support for the development of manufacturing equipment enabling high-speed, low-cost, and uniform deposition of state-of-the-art OLED structures and layers. This includes the development of new tool platforms or the adaptation of existing equipment to better address the requirements of OLED lighting products. Tools under this task should be used to manufacture integrated substrate layers or the OLED stack. Solution or vapor deposition equipment may be explored, but resultant layers must demonstrate the ability to maintain state-of-the-art performance. Overall impact on cost and yield should be considered and equipment should be justified based on a cost-of-ownership analysis and a comparison with existing tools available from foreign sources.	
Metric(s)	**2017 Target(s)**
Initial Capital Cost/Line Capacity	\$100/m^2/year
Minimum Substrate Size	10 x 10 cm
Area Utilization	> 80%
Uptime of Machine	> 80%
Thin-Film Layer Yield	> 75%
Materials Utilization	> 60%

Manufacturing cost reductions are essential. Dramatic cost reductions can be realized through equipment design and various approaches can be explored. Low-volume, low-cost deposition systems have the potential to reduce the initial capital cost, the overall cost of ownership, and also can allow for scaling supply to match the market demand. Other approaches may focus on yield improvements or equipment that reduces costs through improved materials utilization. Work should demonstrate a low cost of entry and explain how initial capital investment is compatible with anticipated market sizes. Further, research should emphasize step-function innovation, beyond simple scaling or incremental improvement. Tools compatible with solution or vapor deposition processes can be explored, but state-of-the-art performance must be maintained. A target for the thin-film layer yield is set for the complete stack, and tools affecting the yield of individual stack layers should consider the impact on overall device yield. Further, approaches that reduce costs despite low yields should be described with a cost-benefit analysis.

M.O3. OLED Substrate and Encapsulation Manufacturing: Support for the development of advanced manufacturing of low-cost, integrated substrates (substrate, light extraction layers, anode, current spreading layers or combination thereof) and/or encapsulation materials. Contemplated approaches should demonstrate the performance of the manufactured materials in a state-of-the- art OLED lighting device and should be justified with a cost-benefit analysis.		
Metric(s)		**2017 Target(s)**
Substrate	Total cost – dressed substrate	$60/m^2$
	Extraction efficiency	50%
	Effective Sheet Resistance	< 1 ohms/square
Encapsulation	Permeability of H_2O	10^{-6} g/m^2/day
	Permeability of O_2	10^{-4}cc/m^2/day/atm
	Cost	$35/m^2

Task M.O3 focuses on the development of processes that facilitate manufacturing of high-quality materials for OLED panels. Since cost reduction is critical, establishing the optimal balance between material quality and cost is of utmost importance. The availability of integrated substrates would be advantageous to panel manufacturers, who would then not be required to invest in the equipment and technology required to produce effective light extraction films and appropriate transparent conductors. However, since the extraction schemes and stack structure are so closely coupled, some participants suggested that fully integrated substrate solutions may not be a realistic approach. Further, they note that the substrate manufacturers are not necessarily well equipped for extraction layer development. Thus, this task supports work for the manufacturing of integrated substrates, as well as components thereof.

Encapsulation also remains a weak link for the industry. Better and cheaper technologies for thin-film encapsulation are needed, especially as the industry transitions to such encapsulation methods.

M.O5. OLED Panel Manufacturing: Support for the development of manufacturing processes for practical OLED panels. Suitable development activities would likely focus on one or more of the following areas:

- Integration of processing steps
- Reliability
- Reproducibility and yield
- Changes in design or process flow to reduce manufacturing costs
- Optimized designs or processes for efficient and low-cost manufacturing

The work should result in higher quality panels, improved color consistency, lower manufacturing costs, and/or higher yields. Panels must have market relevant performance levels. Detailed analysis of actual yield, including catastrophic early failures; main defects; TAC time; material utilization; equipment uptime; and process flow should be performed to identify opportunities for improvements in terms of cost and performance.

Metric(s)		**2017 Target(s)**
Panel Yield		> 75%
Reliability	**Catastrophic Failure**	<1 in 5000
Panel to Panel Reproducibility	**Luminous Emittance Control**	±10% of nominal value
	Color Control – Δu'v'	<0.003
Panel Price		< $200/klm

Task M.O5 is a new task created from discussions at the Manufacturing Workshop. There was a clear consensus that large volume manufacturing is the next critical step for the development of US manufacture of OLEDs. This task therefore seeks the development of manufacturing processes that are compatible with the realization of reproducible and cost-efficient OLED panels with relevant commercial-level performance. Benefits could include: 1) accurate assessment of manufacturing reliability and reproducibility to reveal areas for improvement; 2) evaluation of the U.S. supply chain to reveal any gaps; and 3) realization of OLED panels compatible with luminaire manufacturing.

4 STANDARDS

This section summarizes the different types of standards that are of interest to the SSL industry. These sections emphasize LED standards. OLED technology has not progressed to the point where specific standards are available but efforts are underway to develop technology-specific methods or to include them within existing LED methods, where applicable. This section is not intended to be a complete exposition on the subject, but rather as reference for the ongoing progress in the development of SSL standards. As noted in the previous Roadmap editions, there are several uses of the term "standards" that are frequently used:

- Standardized technology and product definitions
- Minimum performance specifications
- Characterization and test methods
- Standardized reporting and formats: Lighting Facts
- Process standards or “Best Practices”
- Physical dimensional, interface, or interoperability standards

These are generally considered to be *industry* standards, but, any of these general types may eventually become a *regulatory or statutory requirement* having the force of law. They are then variously called “rules,” “regulations,” “codes,” or “specifications.” While not always popular, they do provide a useful framework to keep unsafe or substandard products off the market. Examples might be a safety requirement such as UL-type labeling, which is generally required for electrical products, or a minimum efficiency requirement as may be required by Federal Appliance Efficiency legislation. Usually, such legal standards only appear after some period of maturity in the industry; to enforce them too early may mean stifling beneficial further innovation of the technology.

In the course of introducing SSL to the marketplace, there have been, from time to time, unrealistic or even false claims about product performance or equivalency. DOE has tried to address these problems by supporting the development of various testing standards and methods. However, at this point in the development of LED lighting, some manufacturers have begun to chafe under what they regard as excessive or duplicative requirements for mandatory and other industry listing compliance testing. DOE has begun to address this by convening a group of stakeholders to examine the various needs and find ways to minimize testing time and cost [43].

One specific area of concern has been the definition of product lifetime and economical means to establish it. Again, DOE is working with industry on this issue and has published a number of recommendations for characterizing product reliability. However, using most standard test methods may, because of the low failure rate of LED luminaires, require lengthy testing of a large number of luminaires, and thus is not practical. One way to address this is to examine accelerated testing of subsystems and components together with computer modeling to predict product reliability. This work is being explored by a funded R&D project at RTI and the LED Systems Reliability Consortium, convened by DOE, but much remains to be done.

DOE works with a number of Standards Development Organizations (SDOs) to accelerate the development and implementation of needed SSL standards. DOE provides standards development support to the process, which includes hosting ongoing Workshops to foster coordination and collaboration on related efforts. These Workshops are attended by representatives and committee members from the major standards groups: American National Standards Lighting Group (ANSLG), Illuminating Engineering Society of North America (IES), National Electrical Manufacturers Association (NEMA), National Institute of Standards and Technology (NIST), Underwriters Laboratories, Commission Internationale de l'Eclairage (CIE), CSA International, and International Electrotechnical Commission (IEC). Standards directly related to manufacturing can be numerous and quite detailed, and often fall into the last two categories of processes/best practice and interoperability.

Since most work on standards is and will be done by independent industry groups, the objective of the discussion in this Roadmap was simply to identify likely needs for such standards for SSL manufacturing without trying to define the standard. We are pleased to report good progress on the development of manufacturing standards in this issue, thanks to the work done under the auspices of SEMI.

4.1 SSL Product Definitions

The IES has done considerable work and service to the industry by promulgating RP-16-2010, *Nomenclature and Definitions for Illuminating Engineering*, which defines the components and products relating to LEDs for lighting. Other SDOs have also developed some definitional documents which are in some cases in conflict with the IES definitions, for example, IEC/TS 62504:2011. To avoid confusion, harmonization of these definitions should be a priority for the SDOs and some efforts are underway to do so. This Roadmap uses the RP-16 definitions where they exist. While the Roadmap may occasionally offer up suggestions for additional needs definitions, the work of standardization is best handled within existing SDOs with DOE technical support.

4.2 Minimum Performance Specifications

The Energy Independence and Security Act of 2007 (EISA) and other amendments to the Energy Policy and Conservation Act established mandatory minimum energy efficiency requirements for several lighting technologies such as general service fluorescent lamps, incandescent reflector lamps, general service incandescent lamps, and compact fluorescent lamps. Although currently no federal efficiency standards exist for LED and OLED lighting, minimum energy conservation standards for "general service lamps," including LEDs and OLEDs, will be required. The U.S. Environmental Protection Agency's (EPA's) ENERGY STAR Lamps specification version 1.0,[n] effective September 30, 2014, will have luminous efficacy requirements for LED integral lamps ranging from 40 lm/W to 65 lm/W, depending on the type and wattage of the lamp. For non-directional luminaires, which use LED light engines or integrated GU-24 based LED lamps, the

[n] This document is available at: http://www.energystar.gov/ia/partners/product_specs/program_reqs/ENERGY_STAR_Lamps_V1_Final_Specification.pdf?e77f-4db5.

current ENERGY STAR Luminaires specification, version 1.2,[o] requires minimum source efficacy of 65 lm/W.

The implementation of minimum performance specifications has also been mentioned under the umbrella of standards. These may be either mandatory or voluntary, as noted above, and some may morph from one classification to the other. The most notable are ENERGY STAR (voluntary) and UL (mandatory for many applications). In addition, recently NEMA published the standard SSL 4-2012, which provides suggested minimum performance levels for SSL retrofit products. SSL 4-2012 applies to integral LED lamps, as well as retrofit replacements for standard general service incandescent, decorative, and reflector lamps. The performance criteria include color, light output, operating voltage, lumen maintenance, size, and electrical characteristics. Some specific examples are mentioned in the sections which follow.

Recently, there has been some concern, coming from several quarters, about the testing burden imposed by minimum performance standards. Manufacturers have expressed concern over the number of different tests and measurements they are required to provide, partly through mandatory standards and partly through what is effectively a marketing requirement to participate in the voluntary standards. In addition, there is a concern that there are sometimes conflicting or overlapping requirements that in some cases require duplication of testing. Conversely, some in the SSL domain question if the standards are sufficiently strong to provide direction towards the most energy-efficient products. And, finally, there has been some public resistance to performance standards in general, leading to uncertainty as to how they will be enforced.

4.3 Characterization and Test Methods

In recent years, there has been increasing industry awareness of recommended standard measurement methods such as IES LM-79-2008 (LM-79), *Approved Method for the Electrical and Photometric Testing of Solid State Lighting Devices*, and IES LM-80-2008 (LM-80), *Approved Method for Measuring Lumen Depreciation of LED Light Sources,* for measurement of initial performance and lumen depreciation in LEDs, respectively. An ongoing issue has been how to extrapolate limited LM-80 lumen depreciation measurements to predict LED package lifetime, a very difficult proposition because of widely varying performance of different designs. An IES subcommittee, with DOE support, completed IES TM-21-2011 (TM-21), *Projecting Long Term Lumen Maintenance of LED Light Sources* in July 2011.[p] This document specifies a recommended method for projecting the lumen maintenance of LED light sources based on LM-80 data. Most recently IES LM-84-2014 (LM-84), *Measuring Luminous Flux and Color Maintenance of LED Lamp, Light Engines, and Luminaires,* and IES TM-28-2014 (TM-28), *Projecting Long-Term Luminous Flux Maintenance of LED Lamps and Luminaires,* were completed and provide a recommended method for testing and projecting the lumen maintenance of LED lamps, light engines and luminaires. TM-28 provides two procedures for lumen maintenance projection – the first via direct extrapolation of lumen maintenance measurement

[o] This document is available at:
http://www.energystar.gov/ia/partners/product_specs/program_reqs/Final_Luminaires_V1_2.pdf?73df-6d7f.
[p] The report is available for purchase at:
http://www.ies.org/store/product/projecting-long-term-lumen-maintenance-of-led-light-sources-1253.cfm.

from LM-84 data and the second using a combined extrapolation of LM-84 and LM-80 data. DOE cautions, however, that projections of lumen maintenance do not directly translate into a complete measurement of lifetime for a luminaire or lamp, which may depend on other failure mechanisms.

Issues associated with chromaticity variations in SSL products have been discussed in Section 2.5.1. ANSI C78.377-2011, *Specifications for the Chromaticity of Solid State Lighting Products,* was introduced as a standard for specifying LED binning ranges. In 2010 NEMA published SSL 3-2010, to improve understanding on color specifications between chip manufacturers and luminaire makers. While there have not been any recent releases regarding color, it remains a difficult issue for many applications and work continues in many quarters to find better ways to characterize the color and color shifts over time.

The EPA's ENERGY STAR Program has defined test procedures for determining which LED products are to receive the ENERGY STAR certification. DOE (Regulatory Group) provides ongoing technical support to the ENERGY STAR Program, which has been recently undergoing several procedural modifications. In order for an LED product to receive ENERGY STAR certification, it must be tested at a laboratory holding appropriate accreditation. Qualification criteria for luminous efficacy of nondirectional LED luminaires is a minimum of 65 lm/W for the LED source, as tested in accordance with the IES LM-82-2012 (LM-82) test procedure published in March 2012 [34]. LED source chromaticity, CCT, CRI, and power measurements are also reported via the LM-82 test report. Lumen maintenance measurements must comply with LM-80 and are to be provided by the LED manufacturer. For LED directional luminaires, the LM-79 approved methods and procedures are used for performing measurements of luminous flux, chromaticity, and power consumption of the complete luminaire.

In June of 2014, DOE published its supplemental notice of proposed rulemaking (SNOPR) detailing a test procedure for integrated LED lamps. The purpose of this procedure is to support the implementation of the Lighting Facts label set by the Federal Trade Commission (FTC) under 42 U.S.C. § 6294(a)(6), as well as the upcoming general service lamps rulemaking which includes LED lamps. DOE was required to initiate the rulemaking for general service lamps by January 1st, 2014. (See Section 4.4 below for discussion on the FTC Lighting Facts label.) The SNOPR references LM-79 for measuring the lumen output, input power, and CCT of LED lamps, with some modifications. Further, the SNOPR proposes a new test procedure for measuring the lifetime of LED lamps. The methodology proposed in the SNOPR consists of four main steps: (1) measuring the initial lumen output; (2) operating the lamp for a period of time (test duration); (3) measuring the lumen output at the end of the test duration; and (4) projecting L_{70} using an equation adapted from the underlying exponential decay function in ENERGY STAR's most recent specification for integrated LED lamps, Program Requirements for Lamps (Light Bulbs): Eligibility Criteria – Version 1.0 [44]. This new proposal does not incorporate the use of LM-84 and TM-28, which were published after the release of the LED test procedures SNOPR and represent the most recent guidance for LED lamp lumen maintenance measurement and projection. Both the LED test procedure SNOPR and the new industry standards LM-84 and TM-28 provide testing procedures only for lumen maintenance. Test procedures that incorporate other potential failure mechanisms have yet to be developed. DOE received public comment on the SNOPR, which it continues to review and has not yet issued a final version.

Summaries of current and pending standards related to SSL are available among the technical publications on the DOE SSL website.[q] Appendix A lists current standards as well as several related white papers and standards in development.

4.3.1 Reliability Characterization and Lifetime Definitions

The lack of an agreed definition of LED package or luminaire lifetime has been a continuing problem because of unsubstantiated claims of very long life for LED-based luminaire products. Often these are simply taken from the best-case performance of LED packages operating under moderate drive conditions at room temperature. DOE has attempted to address this lack of clarity (and understanding) with recommendations initially issued in 2010 and subsequently updated with the June 2011 release of a guide, *LED Luminaire Lifetime: Recommendations for Testing and Reporting second edition*,[r] developed jointly with a Next Generation Lighting Industry Alliance (NGLIA) working group. An important message from this work is that more attention should be paid to more fully understand and account for the variety of failure mechanisms that can affect product lifetime. The effort will lead to more realistic claims for luminaire performance, with consequences for market acceptance and the economics of SSL. There is also a good discussion of the nuances of reliability and lifetime characterization for LED packages and LED-based luminaires in the recently issued DOE SSL fact sheet, *Lifetime and Reliability*.[s]

The efforts of this working group continued with the formation of the LED Systems Reliability Consortium (LSRC) in 2012. The LSRC is intended to explore the possibility of developing a database of subsystems, materials, and components, along with a simulation method that would allow a predictive characterization of the reliability of a luminaire product built up from information on the individual elements. The reliability of luminaire systems is very difficult to measure directly, and accelerated testing methods are very elusive since multiple failure mechanisms may be involved. The idea of a simulation approach is to be able to perform accelerated tests on elements of the system, thus shortening the entire process. The LSRC discussions have benefited from work done by Research Triangle Institute under a DOE SSL award on the subject, and a number of failure modes have been identified so far for further investigation. This work confirms the notion that simply relying on LED package lumen depreciation to estimate life is not sufficient.

In the meantime, IEC TC34 has taken up a proposal for a specification based on "Principal Component Reliability" testing, which is a similar approach to that advocated by the LSRC. That work is ongoing.

4.4 Standardized Reporting Formats

This section discusses two types of standardized reporting formats: standardized reporting of luminaire component performance and standardized reporting of end product lighting

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[q] Please visit the DOE EERE website for more information regarding current and pending standards related to SSL: http://energy.gov/eere/buildings/standards-and-test-procedures.

[r] This document is available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/led_luminaire-lifetime-guide_june2011.pdf.

[s] This document is available at: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/life-reliability_fact-sheet.pdf.

performance. Buyers of lighting components continue to ask for a standard reporting format to facilitate the comparison of alternative choices. For example, they have also asserted a need for better reporting standards for drivers. This latter issue was discussed during the November 2010 Roundtable meetings, where it was agreed that standardization in the reporting of driver performance would alleviate the burden of driver testing that currently falls to the luminaire manufacturer. Additional discussions were held at the CALiPER Roundtable meeting but at present no defined format or characterization method has been developed.

A standardized reporting format would also be useful for the end product. Lighting designers, retailers, and specifiers have for some time been calling for just such a standard data format for LED-based luminaires. However, with the rapidly evolving landscape for SSL products, it may be some time before this type of standardization will be possible.

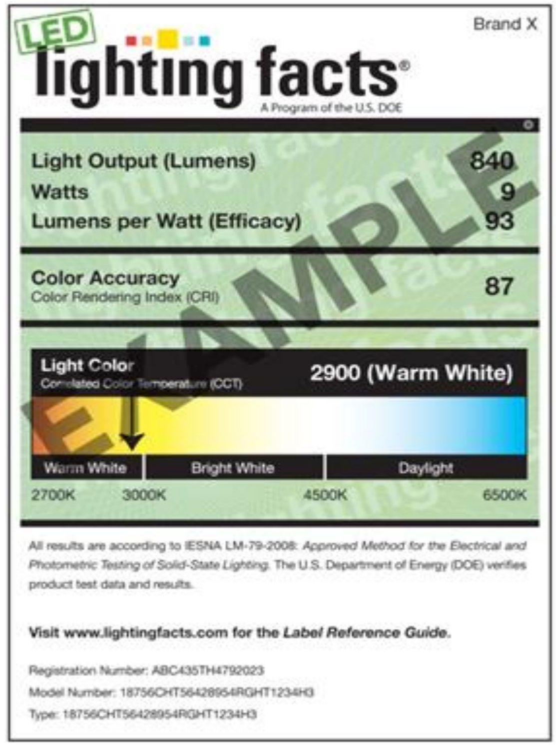

Figure 4.1 DOE Lighting Facts Label Example

Simple labeling standards, however, offer a short-term alternative to help the buyer. DOE recognized the importance of introducing standardized reporting of LED-based lighting product performance for the consumer. In December 2008, LED Lighting Facts, a voluntary program, was created to assure that LED-based lighting products are represented accurately in the market. The LED Lighting Facts label provides a summary of verified product performance data.

The label and on-line registry of over 9,000 products guards against exaggerated claims, and helps ensure a satisfactory experience for lighting buyers. Lamp and luminaire manufacturers who pledge to use the label are required to disclose performance data in five areas – light output (lumens), power consumption (watts), efficacy (lumens per watt), light color (CCT), and color accuracy (CRI) – as measured by the industry standard for testing photometric performance, LM-79. Additional metrics related to reliability, including lumen maintenance and warranty, have been added as optional label metrics. Figure 4.1 shows an example of what the standard LED Lighting Facts label looks like. An optional, extended label is also available to include the new metrics.

The LED Lighting Facts website was recently re-launched as part of the Program's effort to balance the growth of the market with the need for independent verification of reported product performance. Instead of having to test every product to LM-79, manufacturers may test one member of a family and calculate the performance of the related products based on the performance of the tested product. This will go a long way toward reducing the testing burden that has resulted from rapidly expanding and evolving product lines. The balance is maintained by Verification Testing, which allows LED Lighting Facts to preserve its commitment to providing verified data in light of the new testing policies.[t]

Since January 1, 2012, FTC has mandated that all lighting manufacturers incorporate labeling on their medium screw base bulb packaging. The packaging labels emphasize brightness (lumens), annual energy cost, life expectancy (years based on 3 hours/day), color appearance (CCT), power consumption (watts), and whether the bulb contains mercury. The FTC label is primarily a consumer label, while the DOE label is a valuable tool for buyers. In fact, the FTC encourages stakeholders to reference the LED Lighting Facts label, especially as DOE works to improve bulb life testing methodologies for LED lamps [45].

4.5 Interoperability and Physical Standards

Similar to the standardization of reporting formats, there are two categories of interoperability/physical standards. One type is the end-product consumer interface standard, such as the ANSI standards for bulb bases and sockets. These are market-driven standards; compliance with these standards is necessary for success in certain lighting applications. While such standards define the products to be manufactured, and manufacturers certainly need to be involved, they do not directly address the manufacturing process challenges.

The other type includes the interfacing standards that enable complete products or component parts to be interchanged in a seamless fashion. NEMA is currently addressing this issue in part, with its issuance of NEMA LSD 45-2009, *Recommendations for Solid State Lighting Sub-Assembly Interfaces for Luminaires.* Interconnects within an SSL luminaire have an added challenge to manage the thermal aspects of the system in order to keep the LED and electrical components cool enough such that light output and lifetime remain acceptable. The NEMA LSD 45-2009 provides the best industry information available for electrical, mechanical, and thermal SSL luminaire interconnects, and is intended to document existing and up-to-date industry best practices.[u]

The lighting manufacturers have also indicated a strong need for improved interoperability between solid-state lighting products and conventional dimming controls. NEMA SSL-6, *Solid State Lighting for Incandescent Replacement – Dimming*, aims to address some of these issues by providing guidance on the dimming of SSL products and the interaction between the dimmer (control) and the bulb (lamp). However, additional standardization for driver controls is still necessary, as discussed in Appendix A.

In early 2010, an international group of companies from the lighting industry initiated the formation of the Zhaga Consortium, an industry-wide cooperation aimed at the development of standard specifications for LED light engines. Zhaga aims to provide specifications that cover the physical dimensions, as well as the photometric, electrical, and thermal behavior of LED light engines [46].[v]

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[t] More guidance on the LED Lighting Facts® label can be found at: http://lightingfacts.com/Library/Content/Label.

[u] LSD 45 is available as a free download from NEMA at: http://www.nema.org/stds/lsd45.cfm.

[v] Information on the Zhaga Consortium and their interoperability standards can be found at: http://www.zhagastandard.org.

4.6 Process Standards and Best Practices

When the DOE Manufacturing Initiative first began in 2009, there was a great deal of hesitation regarding the development of manufacturing or process standards for LED technology. But gradually as the industry has matured, this perspective has changed, due in large part to the efforts of SEMI and its members, who formed an HB-LED Standards Committee in November of 2010 with strong industry support among device makers, equipment manufacturers, and material suppliers.

Standards for materials and equipment used in manufacturing SSL products allow manufacturers to purchase equipment and materials from multiple vendors at lower cost, improved quality, and with minimum need for modification or adaptation to a particular line. For suppliers to the industry, standards also can reduce the need for excess inventories of many similar yet slightly different materials and parts. Reduced inventory means lower costs and faster deliveries. The SEMI HB-LED Standards Committee has grown to over 120 registered task force members representing key elements of the global manufacturing supply chain for LED lighting products. Published standards include SEMI HB1-0113, Specifications for Sapphire Wafers, and recently SEMI Draft Document 5420A, specifying 150 mm wafer cassettes, has also been approved. Several other activities are under way, as listed in Appendix A.

Appendix A Standards Development for SSL

Because standards development will aid in increasing market confidence in solid-state lighting (SSL) performance, the U.S. Department of Energy (DOE) works closely with a network of standards-setting organizations and offers technical assistance and support. This support includes assessing product performance through testing, statistical evaluation, data collection and analysis, and document development. It is intended to accelerate the development and implementation of needed standards for SSL products.

Below is a summary of current and developing standards and white papers pertaining to SSL.

Current SSL Standards and White Papers

The documents listed below are for information and reference only. Several are not directly related to DOE support work, or may not be applied by the industry at this time.

- **ANSI C78.377-2011, Specifications for the Chromaticity of Solid State Lighting Products,** specifies recommended color ranges for white LEDs with various correlated color temperatures. Color range and color temperature are metrics of critical importance to lighting designers.[w]
- **ANSI C136.37-2011, Solid State Light Sources Used in Roadway and Area Lighting,** defines requirements for SSL fixtures used in roadway and off roadway luminaires, including interchangeability, operating temperature range, chromacity, mounting provisions, and wiring.[x]
- **CIE 127-2007, Measurements of LEDs,** describes the measurement conditions of spectrum, luminous flux, and intensity distribution for individual low-power LED packages.[y]
- **CIE 177-2007, Colour Rendering of White LED Light Sources,** describes the application of existing color rendition metrics to LEDs and recommends the development of improved metrics.[z]
- **IEC/TR 61341:2010, Method of Measurement of Centre Beam Intensity and Beam Angle(s) of Reflector Lamps,** describes the method of measuring and specifying the beam

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[w] A hard copy of C78.377 is available for purchase or as a free download from NEMA at: www.nema.org/stds/ANSI-ANSLG-C78-377.cfm. Hard copies can also be purchased from ANSI at: www.webstore.ansi.org.

[x] An electronic copy of ANSI C136.37-2011 is available for purchase at: http://webstore.ansi.org/RecordDetail.aspx?sku=ANSI+C136.37-2011.

[y] An electronic copy of CIE 127:2007 is available for purchase at: http://www.techstreet.com/cie/products/1371545.

[z] An electronic copy of CIE 177:2007 is available for purchase at: http://www.techstreet.com/cie/products/1320305.

angle and intensity of reflector lamps. This measurement standard applies to LED-based reflector lamps for general lighting purposes.[aa]

- **IEC 62031, LED Modules for General Lighting – Safety Specifications,** describes general and safety requirements for LED modules.[bb]
- **IEC/TS 62504:2011, General lighting - LEDs and LED modules - Terms and definitions**
- **IEC 62560:2011, Self-ballasted LED-lamps for general lighting services by voltage > 50 V - Safety specifications**
- **IEC 62612:2013, Self-ballasted LED lamps for general lighting services with supply voltages > 50 V - Performance requirements**
- **IEC/PAS 62717, LED modules for general lighting - Performance requirements**
- **IES G-2, Guideline for the Application of General Illumination ("White") Light-Emitting Diode (LED) Technologies,** presents technical information and application guidance for LED products.
- **IES LM-79-2008, Approved Method for the Electrical and Photometric Testing of Solid State Lighting Devices,** enables the calculation of LED luminaire efficacy (net light output from the luminaire divided by the input power and measured in lumens per watt). Luminaire efficacy is the most reliable way to measure LED product performance, measuring luminaire performance as a whole instead of relying on traditional methods that separate lamp ratings and fixture efficiency. LM-79 helps establish a foundation for accurate comparisons of luminaire performance, not only for solid-state lighting, but for all sources.[cc]
- **IES LM-80-2008, Approved Method for Measuring Lumen Depreciation of LED Light Sources,** defines a method of testing lamp depreciation. LED packages, like most light sources, fade over time, which is referred to as lumen depreciation. However, because LED packages have a long lifetime in the conventional sense, they may become unusable long before they actually fail, so it is important to have a sense of this mode of failure. LM-80 establishes a standard method for testing LED lumen depreciation. Note that LED source depreciation to a particular level of light, should not be construed as a measure of lifetime for luminaires, however, as other failure modes also exist which can, and in most cases will, shorten that lifetime.
- **IES LM-82-2012, Approved Method for the Characterization of LED Light Engines and LED Lamps for Electrical and Photometric Properties as a Function of Temperature,** provides a method for measuring the lumen degradation of light engine products at various temperatures in support of establishing consistent methods of testing to assist luminaire manufacturers in determining LED luminaire reliability and lifetime characteristics, thus aiding manufacturers in selecting LED light engines and lamps for their luminaires.

[aa] An electronic copy of IEC/TR 61341:2010 is available for purchase at: http://webstore.iec.ch/webstore/webstore.nsf/Artnum_PK/43777.

[bb] An electronic copy of IEC 62031 is available for purchase at: http://webstore.iec.ch/webstore/webstore.nsf/Artnum_PK/38891.

[cc] Electronic copies of LM-79, LM-80, and RP-16 may be purchased online through IES at www.ies.org/store.

- **IES LM-84-2014, Measuring Luminous Flux and Color Maintenance of LED Lamp, Light Engines, and Luminaires,** provides the method for measurement of luminous flux and color maintenance of LED lamps, integrated; LED lamps, non-integrated; LED light engines; and LED luminaires. The method establishes consistent environmental conditions across laboratories to achieve reproducible results and to permit reliable comparison of results.
- **IES RP-16 Addenda a and b, Nomenclature and Definitions for Illuminating Engineering,** provides industry-standard definitions for terminology related to solid-state lighting.
- **IES TM-21-2011, Projecting Long Term Lumen Maintenance of LED Light Sources,** specifies a recommended method for projecting the lumen maintenance of LED light sources based on LM-80-2008 collected data.
- **IES TM-28-2014, Projecting Long-Term Luminous Flux Maintenance of LED Lamps and Luminaires,** provides guidance and recommended procedures for sampling, test intervals and duration, and a method from long term luminous flux maintenance projection for LED lamps and luminaires.
- **NEMA LSD 45-2009, Recommendations for Solid State Lighting Sub-Assembly Interfaces for Luminaires,** provides guidance on the design and construction of interconnects (sockets) for solid-state lighting applications.[dd]
- **NEMA LSD 49-2010, Solid State Lighting for Incandescent Replacement—Best Practices for Dimming,** provides recommendations for the application of dimming for screw-based incandescent replacement solid-state lighting products.
- **NEMA SSL-1-2010, Electronic Drivers for LED Devices, Arrays, or Systems**, provides specifications for and operating characteristics of non-integral electronic drivers (power supplies) for LED devices, arrays, or systems intended for general lighting applications.
- **NEMA SSL 3-2010, High-Power White LED Binning for General Illumination,** provides a consistent format for categorizing (binning) color varieties of LEDs during their production and integration into lighting products.
- **NEMA SSL 4-2012, SSL Retrofit Lamps: Minimum Performance Requirements,** supplies performance standards for integral LED lamps, including color, light output, operating voltage, lumen maintenance, size, and electrical characteristics.
- **NEMA SSL-6-2010, Solid State Lighting for Incandescent Replacement – Dimming,** provides guidance for those seeking to design and build or work with solid-state lighting products intended for retrofit into systems that previously used incandescent screw base lamps. Addresses the dimming of these products and the interaction between the dimmer (control) and the bulb (lamp).
- **SEMI HB1-0113, Specifications for Sapphire Wafers Intended for Use for Manufacturing High Brightness-Light Emitting Diode Devices**
- **NEMA SSL 7A-2013, Phase Cut Dimming for Solid State Lighting: Basic Compatibility** provides compatibility requirements when a forward phase cut dimmer is combined with one or more dimmable LED Light Engines (LLEs).

[dd] LSD 45 and LSD 49 are available as free downloads from NEMA at http://www.nema.org/stds/lsd45.cfm and www.nema.org/stds/lsd49.cfm. SSL 3 is available for purchase at www.nema.org/stds/ssl3.cfm.

- **UL 8750, Safety Standard for Light Emitting Diode (LED) Equipment for Use in Lighting Products,** specifies the minimum safety requirements for SSL components, including LEDs and LED arrays, power supplies, and control circuitry.[ee]
- **UL 1598C, Safety Standard for Light Emitting Diode (LED) Retrofit Luminaire Conversion Kits,** specifies safety requirements for LED products that are meant to replace existing luminaire light sources.

Standards in Development or Under Revision

- **ANSI C82.XX, LED Driver Testing Method.**
- **CIE TC1-69, Color Quality Scale,** provides a more effective method for relating the color characteristics of lighting products including LEDs.
- **CIE TC2-50, Measurement of the Optical Properties of LED Clusters and Arrays.**
- **CIE TC2-63, Optical Measurement of High-Power LEDs.**
- **CIE TC2-64, High Speed Testing Methods for LEDs.**
- **IEC/TS 62504:201x, General lighting - LEDs and LED modules - Terms and definitions.**
- **IEC 62031:201x, LED modules for general lighting - Safety specifications.**
- **IEC 62560:201x, Self-ballasted LED-lamps for general lighting services by voltage > 50 V - Safety specifications.**
- **IEC 62663-1:201x, Non-ballasted LED lamps – Safety specifications.**
- **IEC 62663-2:201x, Non-ballasted LED lamps – Performance requirements.**
- **IEC 62717:201x, LED modules for general lighting - Performance requirements.**
- **IEC 62776:201x, Double-capped LED lamps for general lighting services – Safety specifications.**
- **IEC 62838:201x, Self-ballasted LED lamps for general lighting services with supply voltages not exceeding 50 V a.c. r.m.s. or 120 V ripple free d.c. – Safety specifications.**
- **IEC/TS 62861, Principal component reliability testing for LED-based products.**
- **IEC/62868, Organic light emitting diode (OLED) panels for general lighting < 50 V – Safety specifications.**
- **IEEE P1789, Biological Effects and Health Hazards From Flicker.**
- **IES LM-79-2008, LED luminaire testing,** currently under review.
- **IES LM-80-2008, Lumen degradation testing of LED sources,** currently under review.
- **LM-85, Reliability Performance Tests for LED packages.**
- **LM-86, Remote Phosphor Device Luminous Flux and Color Maintenance Test.**
- **LM-XX4, Approved Method for the Electrical and Photometric Measurements of Organic LED (OLED) Light Sources.**
- **SEMI Draft Document 5420A, Specification for 150 mm Open Plastic and Metal Wafer Cassettes Intended for Use for Manufacturing HB-LED Devices.**

[ee] UL customers can obtain the outline for free (with login) at www.ulstandards.com or for purchase at www.comm-2000.com.

- **SEMI Equipment Automation TF Doc. 5469, Specification for High Brightness LED Manufacturing Equipment Communication Interface (HB-LED ECI).**
- **SEMI Equipment Automation TF Doc 5529, Specification of Job Management and Material Management for High Brightness LED Manufacturing Equipment (HB-LED JMMM)**.
- **TM-26, Estimating the Rated Life of an LED Product** (incorporates lumen degradation and other failure modes).

Over time, these and other standards will remove the guesswork about comparative product performance, making it easier for lighting manufacturers, designers, and specifiers to select the best product for an application. As industry experts continue the painstaking work of standards development, they are contributing to a growing body of information that will help support solid-state lighting innovation, as well as market adoption and growth.[ff]

[ff] For more information on SSL standards, see www.ssl.energy.gov/standards.html.

Appendix B Manufacturing R&D Projects

Currently Funded Projects

Recipient: Cree, Inc.
Title: Low-Cost LED Luminaire for General Illumination
Summary: *The objective of this project is to develop a low-cost LED luminaire providing 90 lumens per watt (LPW) warm white light with a color rendition of 90. This product target is to provide a minimum lifetime of 50,000 hours with a color shift within a 2-step MacAdam ellipse. The cost target of the luminaire is a 30% reduction from the starting baseline of the project while maintaining market leading performance specifications. To meet the goals, the project plan includes a comprehensive approach to address the cost reduction of the various optical, thermal and electrical subsystems in the luminaire without impacting overall system performance.*

Recipient: KLA-Tencor Corporation
Title: High Throughput, High Precision Hot Testing Tool for HBLED Testing
Summary: *The objective of this project is to develop, characterize, and verify a high throughput, precision hot test tool towards the target measurement of one MacAdam ellipse, the color coordinate consistency required to intersect the achromatic side-by-side white lighting application, the largest sector of the lighting market, currently unserved by low-cost, solid-state lighting. The CIE coordinates and efficacy will be measured at precise customer luminaire packaged product operating conditions by producing and measuring at the wafer level the anticipated conditions over a wide range. The recipient proposes to provide this capability for a wide range of LED phosphor products including phosphors using both silicone and Lumiramic sintered ceramics as phosphor binders.*

Recipient: Cree, Inc.
Title: Scalable Light Module for Low-Cost, High Efficiency LED Luminaires
Summary: *The objective of this project is to develop a low-cost, low-profile LED light module architecture to facilitate the assembly of a variety of high-efficacy, broad-area LED luminaires. This versatile light module will be driven by a novel, compact, LED package for a combination of high color rendering index (CRI) and high efficacy over a wide range of color temperatures. The approach is vertically integrated development of the LED component and light module optical, electrical, and mechanical sub-systems for optimal light generation, distribution, extraction, and diffusion while operating at high efficacy and reduced cost.*

Recipient: Eaton Corporation
Title: Print-Based Manufacturing of Integrated, Low Cost, High Performance SSL Luminaires
Summary: *The objective of this project is to develop manufacturing process innovation that allows for LED package, chip, or chip array placement directly on a fixture or heat sink. The approach includes the placement of integrated power electronics. Flexible manufacturing for planar, non-planar and recessed product designs will be investigated through the development of non-traditional thick film processes. The proposed approach allows for cost reductions through improved thermal performance, reduced materials and parts, and enabled automation and manufacturing flexibility*.

Recipient: Philips Lumileds Lighting Company, LLC
Title: Development and Industrialization of InGaN/GaN LEDs on Patterned Sapphire Substrates for Low Cost Emitter Architecture
Summary: *The objective of this project is to establish a low-cost patterned sapphire substrate fabrication process with demonstrated epitaxial growth of InGaN layers capable of producing low-cost, high-efficiency LEDs when combined with chip-on-board packaging techniques. The proposed cost reductions result from the elimination of some of the complex processes associated with current flip-chip technology and by enabling lower cost packaging methods which take advantage of the stability of the sapphire substrate, which is removed in a standard flip-chip device. The potential impact of the approach will be a reduction in the cost of high-brightness LED lamps and modules targeted across a wide range of lighting and illumination applications*.

Recipient: OLEDWorks, LLC
Title: Innovative High-Performance Deposition Technology for Low-Cost Manufacturing of OLED Lighting
Summary: *The project objective is to develop and demonstrate, in production equipment, the innovative high-performance deposition technology required to drive cost reductions of manufacturing OLED lighting. The current high manufacturing cost of OLED lighting is a leading barrier to market acceptance. The proposed deposition technology provides solutions to the two largest parts of the manufacturing cost problem – the expense of organic materials per area of useable product and the depreciation of equipment. The proposed outcome is to supply affordable, high-quality product to help grow the emerging OLED lighting market*.

Recipient: PPG Industries, Inc.
Title: Manufacturing Process for OLED Integrated Substrate
Summary: *The approach is to develop manufacturing processes to enable commercialization of a large area and low‐cost "integrated substrate" for rigid OLED lighting. The integrated substrate product is proposed to consist of a low-cost, float glass substrate combined with a transparent conductive anode film layer, and internal and external light extraction techniques. Availability of a commercial, low-cost substrate will reduce costs of the OLED devices to stimulate marketable product developments and provide a technology base for increased OLED manufacturing capacity as demand grows*.

Appendix C DOE SSL Manufacturing R&D Tasks

The complete list of SSL Manufacturing R&D Tasks developed in 2010 and refined each year is below. Priority tasks for 2014 are indicated with an asterisk.

LED Tasks		
Task		**Description**
***M.L1**	Luminaire Manufacturing	Support for the development of flexible manufacturing of state of the art LED modules, light engines, and luminaires.
M.L2	Driver Manufacturing	Improved design for manufacture for flexibility, reduced parts count and cost, while maintaining performance.
***M.L3**	Test and Inspection Equipment	Support for the development of high-speed, high-resolution, non-destructive test equipment with standardized test procedures and appropriate metrics.
M.L4	Tools for Epitaxial Growth	Tools, processes and precursors to lower cost of ownership and improve uniformity.
M.L5	Wafer Processing Equipment	Tailored tools for improvements in LED wafer processing.
M.L6	LED Packaging	Identify critical issues with back-end processes for packaged LEDs and develop improved processes and/or equipment to optimize quality and consistency and reduce costs.
***M.L7**	Phosphor Manufacturing and Application	Support for the development of efficient manufacturing and improved application of phosphors (including alternative down converters) used in solid-state lighting.

OLED Tasks		
Task		**Description**
***M.O1**	OLED Deposition Equipment	Support for the development of manufacturing equipment enabling high-speed, low-cost, and uniform deposition of state-of-the-art OLED structures and layers.
M.O2	Manufacturing Processes and Yield Improvement	Develop manufacturing processes to improve quality and yield and reduce the cost of OLED products.
***M.O3**	OLED Substrate and Encapsulation	Support for the development of advanced manufacturing of low-cost integrated substrates and encapsulation materials.
M.O4	Back-end Panel Fabrication	Tools and processes for the manufacturing of OLED panels from OLED sheet material.
***M.O5**	OLED Panel Manufacturing	Support for the development of manufacturing processes for practical OLED panels.

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